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NACA

RESEARCH MEMORANDUM

PRELIMINARY SURVEY OF THE AIRCRAFT

FIRE PROBLEM

By Cleveland Laboratory Aircraft
Fire Research Panel

Flight Propulsion Research Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
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SUMMARY

Information relating to aircraft fires has been reviewed to determine what new or further research might lead to a substantial reduction of the aircraft fire hazard in flight and following crashes. An examination of fuels, lubricants, and hydraulic fluids as inflammable liquids is presented herein, together with possible sources of ignition under the general categories of hot surfaces, electric sparks and arcs, flames, and hot gases. The literature on these topics is extensive and a number of organizations are currently engaged in research and development activities on the aircraft fire problem.

A review of the statistics on aircraft accidents shows that about 15 percent of all air-carrier accidents are crashes followed by fire and about 5 percent of all accidents are caused by fire in flight. In 1946, crash fires caused approximately 70 of 251 deaths in air-carrier accidents, and fires in flight were responsible for 22 deaths.

From the existing information, it might be concluded that major reductions in the aircraft fire hazard could be achieved by the use of low-volatility fuel with inerted fuel tanks, noninflammable lubricant, and noninflammable hydraulic fluid. Conclusive demonstration of the apparent benefits in safety to be derived from low-volatility fuel appears necessary, and serviceability must be achieved in the engines that will use a low-volatility fuel to at least the same degree that now exists with aircraft engines. Extensive research and development must proceed before a satisfactory noninflammable lubricant will be achieved. Noninflammable hydraulic fluids are being developed and their effective utilization should be hastened.

The phenomena of fire extinguishment are incompletely understood and should be studied. Adequate methods of detecting fire or combustibles require further development.

There are many existing and potential ignition sources on an aircraft. In order to establish the appropriate remedial measures involving these ignition sources, knowledge on the exact nature of the start and propagation of fires in aircraft must be extended. Information shows that the exhaust system may be the single most dangerous ignition source, particularly in a crash or during a major engine failure, and methods for reducing exhaust-system temperatures should therefore be investigated.

The ultimate reduction of the fire hazard will not result from the application of any single improvement, but will come from an integration into the airplane design and operation of new ideas and methods, many of which remain to be explored.

INTRODUCTION

The loss of nearly 100 lives attributed to fire in air-carrier accidents during 1946 and a similar high toll during 1947 clearly designates the need for minimizing existing aircraft fire hazards. Steady progress in learning methods of prevention, detection, confinement, and extinguishment of aircraft fires, particularly in flight, has been made during recent years as a result of the leadership and efforts of the Civil Aeronautics Administration and the work sponsored and conducted by the Army Air Forces, the Bureau of Aeronautics of the Navy Department, the aircraft and allied industries, the National Fire Protection Association, and the universities. Many of the methods resulting from the combined efforts of these groups are in use.

The urgency of the need to accelerate the rate at which aircraft fire hazards are minimized, however, is evident and can presumably be achieved by both supporting and augmenting the existing programs. An investigation of methods for reducing aircraft fire hazards has therefore been initiated at the NACA Cleveland laboratory.

The first phase of the investigation has been a study and a review by laboratory personnel from Flight, Combustion, and Fuels Branches of information relating to aircraft fires to determine those areas in which substantial reduction of the aircraft fire hazard might result from an extension of existing information or from an exploration of new ideas. A preliminary presentation of the panel study is given in this report.

Considering the many factors involved in the occurrence of aircraft fires in flight or following crash, it is obvious that the task of predicting occasions when fires will or will not result is a somewhat hopeless task. The airplane in flight with its complex internal systems contains many potential ignition sources that are dangerously close to large quantities of inflammable liquid. This situation is obviously aggravated considerably in a crash by virtue of the release of inflammable liquids, the formation of inflammable mixtures, and the presence of various individual sources of ignition. The solution to the problem of eliminating or reducing the fires that occur in flight or after crash can, therefore, best be approached from study of two essential factors involved, namely, combustible mixtures and ignition sources.

Specifically, this report presents an examination of fuels, lubricants, and hydraulic fluids as inflammable liquids together with possible sources of ignition under the general categories of hot surfaces, electric sparks and arcs, flames, and hot gases. Emphasis is placed on conditions that may exist in an aircraft after a crash or in flight.

Literature bearing on the known facts of inflammable liquids and ignition sources and on the relations between inflammable liquids and ignition sources is quite extensive and serves as a sound basis for an examination of the fire problem. As in all problems involving numerous intangible variables, an exact analysis of the fire problem has not been and probably cannot be made. The broad range of subject matter dealing with specific remedial action, such as the effect of details of airplane design on the susceptibility of an airplane to fire and methods of fire extinguishing are not discussed in detail. These subjects will be studied in greater detail as the work progresses. In the discussion an effort has been made to generalize some of the pertinent information regarding inflammable liquids and ignition sources and to suggest lines of new or augmented research activity that should aid in minimizing the aircraft fire hazard.

An examination of the statistics on aircraft accidents is also included in this report. The statistics point out the magnitude of the fire problem as a whole and can be used to establish the relative importance of fire during ground operation, fire during flight, and fire following a crash.

STATISTICS ON AIRCRAFT FIRES

Aircraft accident statistics were reviewed and analyzed in order to determine the frequency with which aircraft fires occur as compared with other aircraft accidents and to determine whether fire during ground operation, flight operation, or following a crash is responsible for the most fatalities. A comparison of these results would then indicate which parts of the aircraft fire problem should receive the maximum research effort.

A study of the 121 United States air-carrier accidents that occurred during 1946 (reference 1) shows that 22, or 18 percent, of these accidents involved fire. The Army Air Forces in a survey of 3635 of their accidents within continental United States (references 2 and 3) found that fire was a factor in 15 percent. These two percentages agree reasonably well, and thus it appears that at the present time, fire will be either the cause or the result in approximately one-fifth of all air-carrier accidents.

The problem of aircraft fires can be divided into three parts: fire during ground operation; fire during flight operation; and, fire following a crash. An analysis of the 11 taxiing accidents listed in reference 1 shows that there were no injuries or fatalities during ground operation and that no fires were involved. This result indicates that fires during ground operation are of minor importance from the standpoint of passengers and personnel. Fires in the air and fires following crash are therefore the two major problems. The British in their analysis of the problem have reached the same conclusion (reference 4).

During the calendar year of 1946, approximately 5 percent (6/121) of all air-carrier accidents were caused by fire in the air. This value agrees well with the results of the Air Force survey given in references 2 and 3; 4 percent of their accidents in 1944 and 5 percent in 1945 were attributed to fire in flight. In the six air-carrier accidents or forced landings caused by fire in the air during 1946, 22 out of the 120 people involved were killed, a fatality rate of approximately 18 percent. In an analysis of data collected from January 1, 1938 to July 1, 1944, McFarland (reference 5) found a fatality rate of 26 percent due to fires in flight. Based on these statistics, the average fatality rate in fire-in-flight accidents may be as high as 25 percent. If it is assumed that the 5 percent of airplanes experiencing fire in flight carry 5 percent of the passengers, approximately 1.5 percent of all passengers involved in accidents are killed because of fire in flight.

The 1946 air-carrier accidents also show that fire followed approximately 13 percent of all the accidents. The Air Force data given in references 2 and 3 indicate that 11 percent of their accidents within continental United States were followed by fires, which substantiates the percentage found for commercial accidents. It may thus be assumed that no more than 15 percent of all accidents are crashes followed by fire. The percentages of fires in flight and following crashes are compared with all other accidents in figure 1.

In determining fatalities chargeable to fire following a crash, accidents involving fire in flight, taxiing, ground operation, and gusts were first excluded from consideration. The remaining accidents were divided into two general groups; accidents followed by fire and accidents not followed by fire. The fatality rate of each group was determined and the difference between them and their ratio to one another can be used as measures of the number of people that were killed by fires following crashes.

The fatality rate of an accident is largely dependent upon its severity; therefore, the average severity of the two groups must be equal if a comparison of their fatality rates is to be valid. Two measures of crash severity are possible; the damage done to the airplane and the number of fatalities experienced. Analyses based on both measures were made and the results are presented for comparison in the following table. The specific accident data upon which each of the analyses is based are presented in tables I to IV.

Accident severity bases	Fatality rates, (percent)			
	Fire following crash	No fire following crash	Chargeable to fire	Ratio of fatality rates (fire/no fire)
Accidents severe enough to completely wash out airplane	65	24	41	2.7
Accidents having at least one fatality	75	44	31	1.7
Accidents having fatalities up to two-thirds of people involved	25	12	13	2.1
Accidents having at least one fatality and at least one survivor	40	12	28	3.3

The table indicates that an average of about 30 percent of the people involved in fire-following-crash accidents are killed by the fire. The ratios show that from two to three times as many people are killed in accidents followed by fire than are killed when no fire follows the accident.

In analyzing aircraft-fire data covering a $6\frac{1}{2}$-year period, McFarland (reference 5) found a 79-percent fatality rate when fire followed crashes and a 50-percent fatality rate in crashes not followed by fire. This analysis indicates a fatality rate of 29 percent chargeable to crash fires, or a fatality-rate ratio of 1.6. Furthermore, the analysis of data submitted by letter from the Civil Aeronautics Administration to the NACA resulted in a fatality-rate ratio of 1.7. These values agree well with the results presented in the preceding table for accidents having at least one fatality. If it is assumed that the 15 percent of airplanes that burned following crashes carried 15 percent of the passengers, approximately 4.5 percent of all persons involved in air-carrier accidents were killed by fire that followed the crash. This fatality rate indicates that approximately 70 lives could have been saved in 1946 if all fires following crashes could have been prevented. A graphic comparison of the fatality rates attributed to fires with total fatalities in 1946 is shown in figure 2.

To summarize briefly, the statistics indicate that approximately 1.5 percent of the passengers involved in accidents were killed as a direct result of fire in the air and that approximately 4.5 percent were killed by fire following a crash. From the standpoint of fatalities, fires following crashes thus appear to be the more important problem at the present time.

Although statistics for 1947 are not yet available, preliminary estimates indicate that the actual fatalities due to fire will be higher than for 1946.

CHARACTERISTICS OF COMBUSTIBLE LIQUIDS

CARRIED IN AIRCRAFT

Fuel and Lubricating Oil

Pertinent combustible liquid characteristics. - Two combustible liquid properties of interest insofar as fire hazards are concerned are flash point and spontaneous-ignition temperature (sometimes called autoignition temperature). The flash point of a combustible liquid can be defined as the temperature to which the liquid must be heated in order to give off sufficient vapor to form an inflammable mixture with air. In laboratory test procedures the spontaneous-ignition temperature is defined as the lowest temperature of a surface on which a combustible vapor-air mixture will ignite after a specified time delay.

Flash points of petroleum products vary over a wide range with the more volatile gasolines and naphthas flashing at temperatures considerably below 0° F, kerosenes in the range from 100° to 160° F, and lubricating oils in the range between 275° and 650° F (reference 6). It is therefore apparent that the less volatile liquids must be heated to higher temperatures in order to produce inflammable vapors. Data from references 7 to 10, which substantiate this relation, are presented in figure 3. This figure shows that liquids having high boiling points also have high flash points, but low Reid vapor pressures (a measure of volatility). Equations for the two curves shown are as follows:

$$t_f = 0.69\ t_{10} - 126 \qquad (1)$$

$$t_{10} = 2102 + \frac{33{,}100}{\log P - 17.7} \qquad (2)$$

where

t_f flash point, °F

t_{10} 10-percent A.S.T.M. distillation point, °F

P Reid vapor pressure, lb/sq in.

The 10-percent point is shown on the abscissa of figure 3 in order to make the chart applicable to gasolines as well as pure hydrocarbons. An A.S.T.M. distillation curve (A.S.T.M. method D 86-40) for an aviation gasoline is shown in figure 4. The 10-percent point refers to the temperature at which 10 percent of the gasoline has been evaporated in a specified laboratory apparatus under controlled conditions. Pure hydrocarbons have flat distillation curves; that is, over the whole range of evaporation the temperature is constant. Consequently, for pure hydrocarbons, 10-percent point and boiling points may be used interchangeably.

The flash points of fuels will vary with altitude, as shown in figure 5. The relation shown in this figure is developed from the following equation (reference 11) and data presented in figure 6.

$$t_f - t_l = 8 + 0.024\ t_{10}$$

where

t_l temperature of lean explosive limit, °F

The slopes of the lines in figure 5 are slightly higher than indicated by actual data presented in figure 3.

For all practical purposes, the flash point determined under sea-level conditions provides a satisfactory index of the tendency of a combustible liquid to form combustible mixtures with air (fig. 5). On this basis alone, it is justifiable to assume that a desirable fuel from the standpoint of fire hazard should have as high a flash point as possible, consistent with the pertinent factors involved in the applicability of such a fuel to aircraft.

Unfortunately, however, the aforementioned spontaneous-ignition temperature behaves in a manner opposite to that of flash point (fig. 7). With this fact in mind, it can be seen that a fuel with a high flash point may show a decreased tendency to form combustible fuel-air mixtures that can be ignited by an external source, but at the same time the fuel may have such a low spontaneous-ignition temperature that ignition can occur by contact between fuel vapors and a moderately hot surface.

This does not mean that a commercial fuel blend having a high flash point will necessarily have a low spontaneous-ignition temperature. In fact, commercial low-volatility fuels (boiling range, 300°-400° F) have both high flash points and high spontaneous-ignition temperatures because many hydrocarbons with high spontaneous-ignition temperatures are contained in such fuels in order to meet antiknock requirements. Further discussion of this point is presented later.

Spontaneous-ignition temperatures reported in the literature (reference 8 and references 12 to 24) are not in agreement in regard to absolute value; however, trends determined in relation to some property of the fuel, such as boiling point, are very consistent. The lack of agreement in absolute values among investigators can be attributed to several factors:

(1) Purity of liquids examined

(2) Composition of the surfaces on which ignition temperatures were determined

(3) Condition of the surfaces on which ignition temperatures were determined

(4) Method of heating surface

(5) Shape, size, and orientation of surface

(6) Fuel-air ratio, or amount of fuel introduced

Spontaneous-ignition temperatures for various hydrocarbons are presented in figure 8. These data were taken from references 8, 12, and 13. The classes of compounds differ greatly in their ignition temperatures and even within the same class of compounds (for example, paraffins) branched structures (fig. 8(b)) have higher ignition temperatures than straight-chain structures.

<u>Significance of combustible liquid characteristics in relation to aircraft fire problem.</u> - In considering aircraft fires, either in crash or in flight, there are innumerable circumstances in which the properties of the combustible liquids present can play an important part. In order to illustrate the behavior of combustible liquids in aircraft fires, several situations have been assumed and an effort has been made to anticipate the role of the combustible liquid on the basis of known facts.

(1) If the atmosphere adjacent to a conventional gasoline is not confined, the mixture in the vicinity of the gasoline is usually combustible. The distance away from the liquid surface over which the mixture is combustible depends upon the extent of the air dilution. This statement is supported by the fact that the flash point of gasoline is about -40° F. The temperature of the atmosphere at sea level, except on rare occasions, is therefore considerably above the flash point of the gasoline. Thus when gasoline may be spilled, as in an airplane crash or gasoline leakage from lines or tanks into open wing spaces, it is almost certain that combustible fuel-air mixtures will be present and will ignite if exposed to a suitable source of ignition.

(2) If at sea level the atmosphere adjacent to a conventional gasoline is confined, as in a fuel tank, the fuel-air mixture over the liquid is not combustible if the fuel temperature in the tank is above approximately 15° F; at higher temperatures, the fuel-air mixture over the liquid fuel in the tank is too "rich" to burn. If, however, the tank is ruptured and this fuel-air mixture escapes to the atmosphere, the mixture is "leaned" to possible combustible mixtures and exposure to suitable sources of ignition will cause a fire. At temperatures between 15° and -50° F, combustible mixtures can and do exist in airplane tanks carrying conventional gasoline at altitudes below 10,000 feet; however, this range varies with altitudes. (See fig. 6.) The combustibility limits shown in this figure were obtained from reference 25 and the shaded area was determined by data from the California Research Corporation.

(3) On the basis of the foregoing discussion, it is apparent that a fuel of lower volatility than conventional gasoline is desirable if the hazard of combustible fuel-air mixtures is to be reduced when fuel is exposed to the atmosphere. In a confined space, however, the fuel-air mixture over liquid low-volatility fuel may be combustible up to an altitude of 10,000 feet, if fuel temperatures in excess of about 80° F are encountered. If fuel temperatures above 80° F are encountered more frequently than temperatures below 20° F, which is the upper limit of inflammability for

conventional gasoline, low-volatility fuel will be a potentially greater hazard in tanks than conventional gasoline. Conversely, if fuel temperatures below 20° F are encountered more frequently than temperatures above 80° F, conventional gasoline will be a potentially greater hazard than low-volatility fuel. In either case, it is significant that gasoline-air mixtures in a tank are not always noncombustible and low-volatility fuel-air mixtures are not always combustible. In other words, the fuel-air mixture within a tank is alternately combustible and noncombustible, depending upon the conditions. From this standpoint, the use of an inerting medium in a fuel tank is justifiable whether the fuel is gasoline or low-volatility fuel.

(4) In the case of spillage of large quantities of fuel that may be exposed to ignition sources, as in the case of an airplane crash, the rate of flame propagation for the fuel is of prime importance in regard to the rapidity of flame spread around or over the wreckage. If the surface temperature of a fuel, whether conventional gasoline or low-volatility fuel, is below the flash point, no flame will travel over the surface. Inasmuch as conventional gasoline spilled in crash would seldom be at a temperature below its flash point (-40° F), rapid flame spread can be expected.

With a low-volatility fuel, the surface temperature of the fuel exposed during crash will be considerably below the flash point (105° F) unless the crash occurs on hot days before the fuel has had sufficient time to cool below its flash point. Fuel in the tanks of parked aircraft may reach temperatures considerably above ambient temperatures on hot days, and thus a low-volatility fuel with a flash point of 105° F could easily be at a temperature above its flash point. Data presented in figure 9 show the variation of fuel temperature during an 82-minute flight. The maximum drop in fuel temperature recorded was about 32° F and was reached 50 minutes after take-off. During descent the fuel temperature began to rise and at landing was about 20° F lower than at take-off. It is therefore apparent that if the temperature of the low-volatility fuel at take-off had been about 140° F, the entire flight could have been made with combustible vapors in the tank.

These data are cited to show that under certain conditions low-volatility fuel may exceed its flash point at the time of crash; as previously stated, however, conventional gasoline is nearly always above its flash point.

Data on the rate of flame propagation over the surface of combustible liquids have been obtained by the Shell Development Company. Part of these data resulted from tests in which 20 gallons of each test fuel were burned in a rectangular concrete trough 30 feet long and 4 feet wide with a fuel depth of about 1/4 inch. In the following table the burning rates for three fuels of different volatility are compared:

Fuel	Vapor pressure (mm Hg)	Burning rate (ft/min)
Gasoline	240	800
Low-volatility fuel	6	35
Dieselene	<0.5	12

These burning rates were measured when the fuels were burning at a wind velocity of about 400 feet per minute (4.5 mph). In tests comparing the influence of burning rates with and against the wind in the same 30-foot trough, the following results were obtained:

Fuel	Burning rate (ft/min)	
	With wind	Against wind
Gasoline	800	400
Low-volatility fuel	30	15

The temperature of the fuel used in these tests was varied from 66° to 90° F. The data indicated that the flame-spread rate is solely a function of fuel vapor pressure. More extensive tests made by the Shell Development Company on a 4-foot tray and with three fuels confirmed this relation. (See fig. 10.) Data from tests with the small tray did not confirm the large-scale tests, in which burning against the wind halved the burning rate. (See fig. 11.) A reduction in wind velocity from 800 to 400 feet per minute (fig. 11) decreased the flame velocity from 41 to 15 feet per minute, a decrease of 64 percent.

In the study of the effects of wind velocity, the Shell Development Company found that the difficulty of ignition, particularly with low-volatility fuels, increases with wind velocity.

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(5) Stagnant combustible mixtures of air and gasoline or oil vapors will ignite if permitted to remain in contact with surfaces having temperatures above about 455° F (reference 20). This limit is not definitely established, however, owing to the number of factors that influence measurements of spontaneous-ignition temperatures.

The general tendency for some parallelism between spontaneous-ignition temperatures and knock ratings of fuels is more relative than absolute. Regardless of this fact, the trends of such data indicate that the higher the knock rating, the higher the spontaneous-ignition temperature. This in itself is a fortunate circumstance inasmuch as high-knock-rating fuel components are needed in order to produce commercial blends in the desired performance grade (100/130). Thus, whether the 100/130 fuel produced is in the gasoline range or the low-volatility fuel range, its spontaneous-ignition temperature would be relatively high. This is substantiated by the following data from the California Research Corporation:

Fuel	Performance grade	Spontaneous-ignition temperature (°F)
AN-F-28	100/130	1030
Paraffinic low-volatility fuel	99/123	1040
Aromatic low-volatility	97/>170	1120
120 grade aviation oil	--------	830

It is interesting to compare these ignition temperatures, which were obtained with laboratory apparatus, with the following average ignition temperatures obtained by splashing fuel on a hot pipe as reported by the Texas Company:

Fuel	Average spontaneous-ignition temperature (within ±100° F)
AN-F-28	1250
Low-volatility fuel (300°-400° F)	1250
120 grade aviation oil	1000

In an investigation reported by the Civil Aeronautics Administration (reference 26) it was found that under operating conditions the highest exhaust-stack temperature encountered for the particular engine studied was 1150° F. At this temperature it can be assumed that gasoline, low-volatility fuel, and lubricating oil would ignite on the stack. Thus, insofar as fuel and exhaust-stack temperature are concerned, low-volatility fuel offers no advantage over conventional gasoline. On the other hand, when the air around the exhaust stack is in motion, as in flight, the Civil Aeronautics Administration data shown in figure 12 for four inflammable liquids indicate that the difficulty of ignition increases as the air flow around the exhaust stack is increased. This fact is consistent with the Shell Development Company data mentioned earlier, in which the difficulty of ignition, particularly with low-volatility fuels, increased with wind velocity. This fact is based on the 30-foot and 4-foot tray tests in which the fuel was ignited by means of a lighted taper or torch.

In addition to these data, the Texas Company has made tests of ignition tendencies of fuels when subjected to different surface conditions. These tests were made by crashing fuel on a concrete platform at selected distances from an ignition source. Ignition tendency was expressed as the temperature differential (A.S.T.M. 10-percent evaporated temperature of the fuel — ambient-air temperature) necessary for ignition to occur. The results, referred to dry-platform conditions, are as follows:

Condition of platform	Change in ignition temperature differential (within ±100° F)
Wet	No effect
Filled with water	No effect
Raining	Decreases by 15°
Filled with snow	Increases by 50°
Filled with sand	Increases by 15°

The fuels used were blends of aviation gasoline and a commercial solvent.

In connection with spontaneous ignition of fuels and oils, the Civil Aeronautics Administration (reference 26) found that after a fire occurred the heat from the fire had raised the temperature of the exhaust stack to 1400° F. Below this temperature, laboratory tests showed that SAE No. 10 oil would not ignite on a steel plate but that oil vapor would ignite at temperatures as low as 750° F.

Hydraulic Fluids

The use of hydraulic-control systems in aircraft presents another serious problem in regard to fire hazard, in that additional hydrocarbon oils are present under high pressure and may possibly be exposed to ignition sources. This problem has been extensively investigated at the Naval Research Laboratory (references 27 and 28) since 1941. The research on this problem has been directed toward the achievement of less-inflammable and noninflammable hydraulic fluids and much of the information obtained is directly applicable to the search for less hazardous lubricating oils. In particular, flammability characteristics have been reported (reference 27) for organic phosphates, carbonates, silicone fluids, Ucon fluids (Carbide and Carbon Chemicals Corporation), glycols, and aqueous glycol solutions. Additional data were obtained on the effects of chlorination on inflammability.

The results of this work (references 27 and 28) indicate that the following fluid types are unsuitable as noninflammable hydraulic fluids:

(a) Petroleum fractions with or without oxidation inhibitors

(b) Petroleum fractions containing various volatile organic flame-resistant additives to serve as fire chokers or quenchers

(c) Phosphoric-acid esters such as trioctyl phosphate, tributyl phosphate, and tricresyl phosphate

(d) Mixtures of organic solvents such as alcohols, ethers, and alcohol-ethers thickened to the desired viscosity with blown castor oil

(e) Esters of dibasic acids, especially those having extremely low volatilities

The following less flammable fluid types showed promise as hydraulic fluids:

(a) The chlorinated or fluorinated hydrocarbons and ethers containing approximately three atoms of halogen per molecule (for the substances studied, this was equivalent to nearly 50-percent halogenation of the compound)

(b) The silicones with viscosities of over 20 centistokes at 100° F, if properly stripped of volatile fractions or impurities. The substances particularly of interest here are the polymethylsiloxanes and the copolymers, the poly- (methyl, phenyl) siloxanes.

(c) Certain polyalkylene oxides

(d) The glycols containing high percentages of oxygen

(e) Certain aqueous organic solutions containing sufficiently high proportions of water to render them noninflammable.

Consideration (reference 28) of such factors as effects on packings, volatility, flash point, desired viscosity index, and availability led to the conclusion that an ethylene-glycol-water mixture provides the most promising possibility for obtaining a less inflammable hydraulic fluid in the near future and service tests are now in progress. It is indicated, however, that the other promising noninflammable hydraulic fluids examined in this study (reference 28) may, after extensive development, be applicable to aircraft.

In addition to the foregoing investigation, the Civil Aeronautics Administration has conducted a study of the inflammability characteristics of certain hydraulic fluids (reference 29). The fluids examined were released at pressures of 1000 and 3000 pounds per square inch and exposed to ignition by exhaust flames, hot exhaust stack, ignition spark, and burning gasoline. Also, crash tests were simulated by ejecting the fluids at 3000 pounds per square inch through an electric arc and oxyacetylene flame.

Seven fluids were tested (reference 29) in comparison with standard aircraft hydraulic fluid and all seven showed less tendency to ignite than did the standard fluid. However, with the exception of a fluid consisting of ethylene glycol, water, and additives, these fluids would ignite under some of these conditions. The ethylene-glycol-water mixture is inflammable after expulsion of the water.

Extinguishing

The degree of freedom from fire likely to be achieved in aircraft will not preclude the use of fire extinguishing equipment. Research and development have been sponsored by the U. S. Air Forces, Bureau of Aeronautics, Bureau of Mines, and the Civil Aeronautics Administration, at government laboratories and private laboratories, whereby the practices of fire extinguishing may be advanced. In addition, investigations reported by the British (reference 4) have contained many recommendations regarding the extinguishing of aircraft fires.

The extinguishing investigations conducted by the Civil Aeronautics Administration (references 26, 30, and 31) are primarily concerned with the effectiveness of various extinguishing agents and the quantities required, rates of application, and optimum methods of distribution when applied to gasoline and oil fires occurring in flight. The conclusions drawn in reference 26 are indicative of the scope of the Civil Aeronautics Administration studies and are of considerable interest in relation to the problem of extinguishing fires in flight. These conclusions are as follows:

1. Extinguishment of most aircraft-power-plant gasoline and oil fires occurring in flight can be accomplished within reasonable weight limitations, provided that adequate rates of extinguishing-agent application and optimum distribution methods are used and provided further that gasoline flow is shut off before extinguishment is attempted.

2. Extinguishment of oil fires occurring in flight can be accomplished without stopping the oil flow but oil shut-off is advisable to prevent recurrence of the fire.

3. Air blast is the most serious factor to overcome in the extinguishment of aircraft-power-plant fires, and is overcome by using adequate rates of agent application.

4. Gasoline fires are more difficult to extinguish in the accessory section than oil fires.

5. The safety-fuel fires in the tests were as difficult to extinguish as fires burning 87-octane aviation gasoline.

6. Within limits, large fires are no more difficult to extinguish than small fires.

7. The power section, the accessory section, the oil cooler, and the exhaust-stack well must be individually protected against fire.

8. The extinguishing agent in the power and accessory sections, and all other locations, should be simultaneously discharged.

9. Tests indicated that wheel-well protection is unnecessary, provided the firewall is leakproof.

10. The discharge of extinguishing agent from the power section is necessary to extinguish accessory-section fires.

11. Tests indicated that methyl bromide and carbon dioxide are the only extinguishing agents of those tested that are satisfactory for general protection against fires in flight in the type of power-plant installation tested. Methyl bromide was found to be the most satisfactory agent from the fire-extinguishing standpoint.

12. The rate of extinguishing-agent application is the most important factor in the application of an extinguishing agent. For the entire engine installation, a rate of application of 9 pounds per second of methyl bromide or 10.8 pounds per second of carbon dioxide is required.

13. The minimum duration of extinguishing-agent application should be approximately 2 seconds.

14. Tests indicated that application of the extinguishing agent ahead of the engine cylinders is ineffective and unnecessary.

In regard to conclusion 5, it was found (reference 26) that in an air blast, low-volatility-fuel fires were as difficult to extinguish as the gasoline fires. This result is contrary to results of tests conducted by the Texas Company on crashing fuels in a 10-mile-per-hour wind.

The first of the following tables indicates the influence of water pressure at the nozzle on the time required to extinguish burning fuel. The other tables show the times required to extinguish 2-gallon samples of fuels of varying volatility.

EXTINGUISHING 300°-400° F ALKYLATE WITH WATER

[$1\frac{1}{2}$-inch Rockwood fog nozzle]

Fog-nozzle pressure (lb/sq in.)	Extinguishing time (sec)
50	27
100	14
125	16

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EXTINGUISHING VARIOUS FUELS WITH WATER

[$1\frac{1}{2}$-inch Rockwood fog nozzle]

Fuel	Extinguishing time (sec)
100/130 grade aviation gasoline	[a]42
200°-300° F fuel	34
250°-350° F fuel	25
300°-400° F fuel	[b]14

[a]Check run, 36 seconds.
[b]Check run, 18 seconds.

EXTINGUISHING VARIOUS FUELS WITH DIFFERENT AGENTS

Fuel	Extinguishing time (sec)	Extinguishing agent
100/130 grade aviation gasoline	50	Stable foam
300°-400° F fuel	28	Stable foam
100/130 grade aviation gasoline	37	Carbon dioxide
300°-400° F fuel	6	Carbon dioxide

It will be observed in the foregoing data that in every case, fires from fuels of lower volatility were extinguished more quickly than fire from gasoline.

In reference 32 the Civil Aeronautics Administration has summarized the findings presented in references 26, 30, and 31 in an effort to present concisely the details of fire extinguishing needed for application by aircraft design engineers. This summary itemizes the potential zones of fire determined from 3000 fire tests on two radial engines, one of which was a 14-cylinder double-row type and the other a seven-cylinder single-row type. Also itemized are the modes of protection recommended for each of these zones and equations are given for computation of quantities of methyl bromide or carbon dioxide required for certain zones. Similar recommendations are given for design and location of fire-detecting devices.

Although the literature on extinguishing is quite extensive, the achievements in the field appear to be predominately the result of applied investigation rather than fundamental. The action of most fire-extinguishing agents has been explained as the cooling 929
of a combustible mixture below the ignition temperature or the blanketing of the fuel with an inert material so as to exclude oxygen from the area involved. In addition to these actions, one investigation (reference 33) has indicated that aqueous solutions of certain salts in small concentrations will extinguish fires. These investigators stated that the fire extinguishing action was not one of cooling or oxygen dilution, but could be explained only on the basis of a salt influencing the combustion process. Other investigators have also reported that the extinguishing action of certain materials is greater than can be accounted for by dilution of oxygen, and that the extinguishing effect differs with different chemicals. Cameron (reference 34) states that combustibles will not burn in an atmosphere containing 6 to 15 percent carbon dioxide, depending upon the combustible, whereas only 3 to 6 percent of methyl bromide is required for extinguishing. In another case (reference 35) 15 percent by weight of methyl bromide was required to extinguish a standard gasoline wind-tunnel fire, which required 45 percent of carbon dioxide for extinguishing.

In still another case, the Bureau of Mines (reference 36) reported that 26 percent by volume of carbon dioxide will inert an isobutane-air mixture, whereas 40 percent of nitrogen is required. These cases indicate that various materials influence the combustion process in addition to the blanketing action that they exert.

Regardless of the nature of the available data on extinguishing, that is, whether such data were obtained by applied or fundamental investigation, the known facts on the subject are extensive and of inestimable value to aircraft designers. Additional studies of the fundamental effects of extinguishing agents on basic combustion reactions will be required before the basic mechanisms of extinguishing are completely understood.

Detection

Concomitant with extinguishing is detection of fire or combustible mixture. The need for reliable and immediate fire detection has been universally recognized. Means have been proposed for the detection of a predetermined high compartment-temperature level, high rate of rise of compartment temperature, flame, smoke, and combustible vapor.

Predetermined temperature levels may be detected by the use of electric switches actuated by fusible-metal-alloy links or other devices, bimetal actuated electric switches, thermoelectric-effect and relay switches, low-melting-temperature insulating material that allows an electric circuit to close when heated above a predetermined temperature level, explosive-charge actuated devices, and liquid-filled capsule or tube actuating devices. High compartment temperature rate of rise may be detected by the use of bimetal switches or thermocouple circuits. Flame may be detected by the use of photoelectric cells that are insensitive to daylight or heat, electronically coupled with necessary indicating devices; electrical conduction through an ionized gas; and fuses of combustible material. Smoke may be detected by the use of photoelectric devices in which light is attenuated by the presence of smoke in a compartment. Combustible vapors may be detected by the use of devices that catalytically cause the combustion of a very small part of the vapor and produce a small temperature rise.

The development of detection devices has been sponsored by the U. S. Air Forces, the Bureau of Aeronautics, and the Civil Aeronautics Administration in numerous private manufacturing concerns. The Air Materiel Command of the U. S. Air Forces currently reports that no completely satisfactory system or device has yet been developed.

The indication of a high temperature level by the use of bimetal actuated electric switches appears to be the most reliable and therefore the most practical means at the present time. In reaching this conclusion, infallibility has been the principal criterion of merit of the various devices. Rate-of-temperature-rise detectors are inclined to give false warnings for some normal engine operating conditions. Thermoelectric devices are delicate and complicated. It is recognized that the use of continuous strip sensing elements are desirable because by such means the greatest part of a compartment can be guarded. If individual point sensing elements are employed, a large number must be used.

An important advantage of the high temperature level detector is that this device also may indicate some types of engine malfunctioning, which, if permitted to continue, would result in a fire or other serious calamity.

Existing smoke detectors have been found only partly satisfactory because they give a warning when water clouds or carbon dioxide clouds are present in sufficient concentration to attenuate the light to the photoelectric cell. Such has been the case in baggage compartments in which dry ice has been used as a cargo cooling agent.

Combustible-vapor detectors have been found unsatisfactory because of the fragile and unreliable nature of existing devices.

The continuance of the vigorous development effort now in progress can be expected to result in improvement in the detection of fire or excessive temperatures in vulnerable compartments in the airplane. A study of the fire problem indicates that as the potency of the existing combustibles is reduced, as ignition sources are eliminated, and when compartmentation and configuration are more conducive to greater fire safety, the problem of detection will be significantly reduced.

Summary Statement Regarding Combustible Liquids and Aircraft Fire Problem

At first glance many of the points discussed in the foregoing sections appear to be contradictory. Actually these contradictions may be attributed to the conditions used by the various investigators. In most cases, however, these differences in conditions have no serious effect on the conclusions that may be drawn, but the application of a particular conclusion to the aircraft fire problem must be considered from two possible viewpoints: fire in flight and fire after crash. The following conclusions indicated by the data are so given:

Fire in flight. -

1. Combustible mixtures will probably exist more frequently in aircraft tanks containing low-volatility fuel than in tanks containing conventional gasoline. It is emphasized, however, that even with gasoline the fuel-air mixture in a tank is not always noncombustible.

2. In stagnant-air spaces (unconfined) in which fuel may be present and exposed to ignition sources, low-volatility fuel is more difficult to ignite and will propagate flame less rapidly than gasoline.

3. In an air blast, fires resulting from low-volatility fuels are as difficult to extinguish as fires from gasoline.

4. In stagnant-air spaces, fires resulting from low-volatility fuels are easier to extinguish than fires from gasoline.

Fire after crash. -

1. When conventional gasoline is spilled, as in the case of an airplane crash or of gasoline leakage from lines into unconfined areas of an airplane structure, it is almost certain that combustible fuel-air mixtures will be present and will ignite if exposed to a suitable source of ignition.

2. Low-volatility fuel will not ignite as readily as gasoline, if spilled during crash and exposed to a suitable ignition source, unless conditions are such that all or part of the low-volatility fuel is above the flash-point temperature (about 105° F).

3. At sea-level conditions and wind velocities less than 5 miles per hour, low-volatility fuel fires spread at a considerably lower rate than gasoline, with or against the wind.

4. If splashed on hot surfaces, oil will ignite at surface temperatures lower than those for low-volatility fuel and gasoline. Low-volatility fuel and gasoline are about equal in this respect.

5. Limited tests indicate that gasoline and a gasoline-solvent blend splashed in the open have an increased tendency to ignite in rain. The ignition tendency is decreased if fuel is splashed on snow or sand. No effect was noticed on water or a wet surface.

6. In still air, a low-volatility fuel fire is more easily extinguished than a gasoline fire.

The data also indicate that a less inflammable or noninflammable lubricating oil is desirable and the attainment of such an oil is possible in light of recent developments in hydraulic fluids discussed in the succeeding section.

The adaptation of less-inflammable or noninflammable liquids to use in aircraft will probably require considerable development work; however, no insurmountable obstacles are foreseen. Considerable data on the merits of low-volatility fuels in regard to antiknock behavior have been published. Data on the possibilities of fuel-injection systems also exist and such systems have been operated successfully. Moreover, the use of fuel injection eliminates the carburetor system now utilized in aircraft and thereby eliminates another potential fire hazard.

CHARACTERISTICS OF POSSIBLE IGNITION SOURCES

Insofar as fire hazards are concerned, ignition sources are of equal importance with the characteristics of combustible liquids. Most ignition sources can be classified in general as hot surfaces, electric sparks and arcs, flame, or hot gases. A few miscellaneous sources do not fit rigorously into one of these four groups, and certain aircraft components or systems such as the exhaust system may provide ignition sources in two or three of these groups. Some of the sources are always present; others require rupturing of a wire, malfunctioning of equipment, or other accidental event to become active. The following survey of ignition sources is incomplete, but serves as a basis for determining where attention might be directed in any attempt to substantially reduce fire hazards.

Hot Surfaces

A large number of probable hot-surface ignition sources exist on the typical present-day aircraft; exhaust ducts, combustion heaters, short-circuited wiring, and friction-heated parts are typical examples. In considering when a hot surface is an ignition source, it is noted from the preceding section that surfaces having temperatures as low as about 455° F have ignited stagnant combustible mixtures of air and gasoline or oil vapors, but spontaneous-ignition temperatures are markedly affected by such local factors as the nature and condition of the hot surface, the composition of the combustible mixture, and the time of content.

Because an almost infinite number of combinations of local factors can be encountered in the design of an aircraft or in the event of a crash, a consideration of hot surfaces as ignition sources should be based on the lowest ignition temperatures known for the combustibles carried in the aircraft.

Exhaust system. - Four parts of the exhaust system may be considered as hot-surface ignition sources: the exhaust ducting, the exhaust valve, the piston head, and the cylinder head, both interior and exterior.

The temperatures of the exhaust duct and the exhaust valve are well in excess of the minimum ignition temperatures of gasoline-air mixtures, as shown by the exhaust-duct temperatures of 675° to 1020° F cited in reference 37 or 1150° F cited in reference 26 and exhaust-valve temperatures of 1140° to 1300° F in reference 38. Piston-head temperatures will normally run below minimum ignition temperatures, but may reach ignition temperatures when the engine is operated at take-off or emergency power. Reference 39 indicates that piston-head temperatures may normally operate between 325° to 465° F. It is improbable that the exterior surfaces of cylinder heads would act as ignition sources because they normally operate below 400° F, with maximum cylinder-head temperatures usually limited to 450° or 500° F.

The high temperature and the exposed location of the exhaust ducting marks it as one of the most likely ignition sources on the aircraft, and past experience shows that many aircraft fires have been started by the exhaust ducting. Numerous examples of fires caused by the presence or the failure of the exhaust ducting are known and in reference 26 it was concluded after a long series of tests that "the most dangerous source of oil ignition in an aircraft power-plant installation is an exhaust system employing shrouds, muffs, and baffles for collecting heated carburetor air." Such baffles enclose a relatively stagnant body of air and result in ignition when well ventilated surfaces do not.

The role of the exhaust valve and combustion chamber as an ignition source is not so obvious, except that exhaust valves are sufficiently hot to be classified as potential ignition sources. An engine that is forcibly stopped, as in a crash, may have been functioning normally up to the instant it is stopped. Such an engine will have at least one cylinder freshly charged with fuel and the intake valve still open. With both the entire combustion chamber and the exhaust valve at high temperature, the fresh charge is almost sure to ignite and the flame could spread back through the entire induction system. This flame may then set fire to fuel released by the crash. A French writer (reference 40) points out that sudden changes in speed, such as might take place when a propeller strikes the ground in a crash, are accompanied by backfires that are a fire hazard. The occurrence of such backfires may be explained by the aforementioned process.

Combustion heaters. - Gasoline combustion heaters provide heated surfaces very similar to exhaust ducts. The walls of combustion heaters are generally of a fairly light gage metal, easily broken in an accident. A heater may be adequately lagged for normal operation, but destruction of the outside lagging or of the unit itself in an accident may expose surfaces hot enough to act as ignition sources. It should also be pointed out that, in present aircraft, gasoline is piped throughout the aircraft to supply the combustion heaters. The status of the combustion heater as concerned with fire, however, has not been completely studied.

Electrical equipment. - Electrical equipment such as motors and generators, short-circuited wires, or loose connections may also provide hot-surface ignition sources.

Modern aircraft make use of many electric motors for operating auxiliary equipment of which fuel pumps, cowl-flap actuators, air dampers, blowers, landing-gear retracting mechanisms and starting motors are representative examples. Not all of these motors are explosion proof, nor is there any requirement that these motors not act as either arc or hot-surface ignition sources. Data in reference 41, when extrapolated, show that if the rotor of a small aircraft motor is locked it can reach temperatures as high as 450° F in less than a minute with an impressed potential of 29.5 volts.

The general rules for operating engine starting motors specify alternate operating and cooling cycles of 1-minute duration. Literature surveyed to date does not show whether such operation will keep the maximum temperature below the spontaneous-ignition temperature of fuel or oil, and the starting-motor specifications reviewed do not definitely state that they are explosion proof.

Large aircraft generators are normally cooled by blast tubes, which take ram air from well forward in the cowling. Reference 42 shows that at about 110 percent of rating the hot-spot temperature of a generator was 446° F and points out that commutators must be designed to withstand temperatures up to 482° F (250° C). Commercial generators are usually protected from extreme overloads by current-limiting regulators and should therefore not overheat. Thus a generator would not normally be an ignition source in flight; however, during crash conditions, if the generator has been under heavy load or has been malfunctioning and the engine is suddenly stopped, the generator could conceivably act as a hot-surface ignition source.

The Bureau of Mines has shown that a light bulb filament greater than 0.0068 inch in diameter heated to over 3000° F will consistently ignite natural gas-air mixtures (reference 43). In another series of tests (reference 21), nickel wires 0.040 inch in diameter ignited methane-air mixtures at temperatures as low as 1470° F, which is below the melting point of copper. Because gasoline-air mixtures have lower ignition temperatures than natural gas or methane-air mixtures, there is the possibility that a bare short-circuited wire will ignite a combustible mixture. The influence of fire-resistant or charred insulation on the tendency of the wire to act as an ignitor is not definitely known.

Normally, the electrical system can be protected by circuit breakers or fuses. In a crash, however, it is possible that such equipment may no longer protect the system. These protective units may also be deliberately or accidentally bypassed by operating personnel. The wiring system in many airplanes also includes an unprotected conductor between the battery and the breaker box and another such conductor between the pilot compartment and the contactor that disconnects the battery from the breaker box.

Friction-heated surfaces and hot particles. - Hot surfaces and hot particles (sparks) may be produced by friction and mechanical interference in a malfunctioning engine or by an airplane sliding along the ground. Surfaces heated by friction will have essentially the same general ignition characteristics as surfaces heated by other means and need no further discussion. When both the aircraft structure and the ground are considered, many materials may strike and produce a spark.

It is apparent from the work of different investigators that hot particles may or may not be ignition sources, depending upon their temperature and size and the relative velocity between the combustible mixture and the particles. The British reported in reference 19 that they were unable to ignite a gasoline-air mixture with steel-to-steel sparks produced by a rotating, 2-inch-diameter, serrated, hardened steel wheel in contact with a hardened, chisel-pointed rod. Heating a rod to a dull red heat and grinding sparks from it with the same serrated wheel likewise failed to ignite the mixture, nor did steel-emery-wheel sparks provide ignition. These tests were considered inconclusive, however, because it was not definitely established that the most easily ignited mixture had been used. White and Price (reference 44) state that steel-to-steel, emery-to-steel, and pyrites-to-steel sparks would not ignite combustible ether-alcohol-air and acetone-air mixtures, but that ferro-cerium to steel sparks readily ignited most mixtures. It is possible, however, that the sparks studied in these two series of tests were not large enough or of high enough temperature to serve as ignition sources.

Silver, Patterson, and others have studied the ignition of inflammable gases by hot moving particles of larger size. Silver (reference 22), in a study using both platinum and quartz spheres of diameters from 0.043 to 0.216 inch, and combustible pentane, hydrogen, and coal gas mixtures, found that in every case the minimum ignition temperature varied greatly with the size of the sphere, diminishing with increase in sphere diameter, although less rapidly as the size increased. Ignition temperatures ranged from 200° to 650° F above the ignition temperature of the mixture as determined by other means. In another series of tests (reference 23), Patterson found there was a minimum ignition temperature for a given size of sphere below which no ignition was obtained. This temperature appeared independent of the richness of the mixture, of the "age" of the sphere, and of its material, so far as this was varied (quartz and platinum). The ignition temperature was well above those indicated by the more usual sources of ignition. It was also found that the ignition temperature increased with increased relative velocity between the mixture and the sphere and that this relation was roughly linear.

No data have been found that give the relations among particle size, particle temperature, relative velocity, and fuel-air ratio for the various aircraft materials and combustibles, nor are the particle sizes involved in engine destruction and accident abrasion known. It is therefore impossible at this time to evaluate completely the importance of hot particles as ignition sources for aircraft fires. In the British spark tests, the hot particles were not of the size or the temperature to cause ignition. Other studies have shown, however, that hot sparks under appropriate conditions will be ignition sources.

The rupture of metallic parts is known to produce heat and also static electricity (reference 45). The British Air Ministry ran tests, in which piano steel wires 0.015 and 0.030 inch in diameter suddenly broke in a mixture of gasoline and air, to determine whether such rupture would cause ignition. No ignition was obtained. They also point out that "a rise in temperature takes place during the elongation before fracture of a tensile test piece depending on the material and the speed of application of the load, but in an extreme case seldom exceeds 100° C." It is therefore considered that simple rupture of structural or mechanical members is not an important ignition source.

Electric Sparks and Arcs

The three general primary sources of electrical energy in an aircraft are engine-driven and auxiliary-power-plant driven generators, the ignition system, and static electricity generated in several ways. Several secondary sources also exist, which contain stored energy that can reappear as electrical energy, namely: the battery, the radio, radar, wiring and electrical components that contain inductive energy, and moving parts such as motor armatures, which contain kinetic energy. These sources may be important ignition hazards during accidents.

The quantity of energy required to ignite a combustible mixture by electric spark at atmospheric pressure is small.

Guest (reference 46), in considering explosions in hospital operating rooms, munitions works, rubber and plastics manufacturing plants, and many industries where flammable vapors and dusts are present, observed from the work of other investigators that for certain gas mixtures an energy of 0.002 joule is required in a spark to cause ignition. Reference 47 shows that magnesium power requires an 0.11-joule spark if ignition is to be certain, although ignition is frequent with sparks of much lower energy content and ignition was occasionally obtained with sparks of about 0.03 joule.

Lewis and von Elbe (reference 48) have shown that 0.0005 joule is the minimum spark energy required to ignite a stoichiometric mixture of natural gas and air at 1 atmosphere with electrode spacings of at least 0.1 inch.

The present 28-volt aircraft system is capable of producing sparks or arcs containing energy far in excess of the minimum required to ignite gasoline-air mixtures. Arcing occurs across the brushes of rotating electric-current equipment, both motors and generators, and could ignite a combustible mixture if it reached the arc.

The present radio shielding of the engine ignition system precludes much possibility of its acting as an ignition source during normal operation or after the engines have stopped.

The dangers of static-electricity discharge during ground operations are well known and have been discussed in the literature (for example, reference 49), but the dangers of such discharges during flight or an accident are not frequently considered.

References 50 and 51, which are reports on radio-interference research conducted by the Army and Navy, state that an aircraft can be charged by contact with airborne particles such as snow, ice crystals, hail, rain, clouds, smoke, and dust. Individual parts of the airplane may also become charged with respect to one another by induction as the aircraft flies near clouds (reference 51). Additional ways in which the aircraft in part or as a whole may become charged are described in reference 45. The rate of rise of potential may be in the order of 200,000 volts or more per second when the aircraft first encounters precipitation static (reference 52) and potentials of 500,000 volts have been recorded. It has also been shown shown that the capacitance of a plane is approximately 20 percent of its wing span in centimeters (reference 50). A simple calculation then indicates that the static charge on a representative commercial aircraft could supply thousands of times the minimum energy required for ignition; however, the hazard exists only when spark discharge occurs. This discharge can take place when the plane touches the ground or when a sudden shift of induced potential from one part of the aircraft to another occurs, as might happen when lightning discharges a cloud adjacent to the aircraft. 629

The Bureau of Mines has measured the electrical capacity of a human being (reference 47), and, assuming that the person were charged to only 10,000 volts, have calculated an electrical energy content of at least 0.015 joule, which could be given up in a spark discharge. Inasmuch as this quantity of energy is several times that required for ignition, passengers insulated from the structure by fabric matting and upholstering may also be considered as potential ignition sources.

Static electricity is generated by the flow of fluids from tubes and can reach dangerous electrical potentials, as pointed out in reference 45. Potentials of 3000 or 4000 volts are easily obtained when petroleum products flow in tubes. This phenomenon can be a fire hazard when fuel tanks are being filled, if the aircraft is not grounded, or when fuel is being dumped in flight.

The chemical energy stored in the battery, the inductive energy stored in the electric circuits of radio and radar, the inductive energy stored in representative electric circuits under load, and the inductive plus kinetic energy stored in equipment like electric motors can easily provide a spark of intensity greater than the minimum required for ignition. Recognizing this potential hazard in the event of a crash, the British have devised a switch that removes the battery from the circuits upon impact (reference 4). The ignition potential of airborne radio and radar equipment has been studied by the Underwriters Laboratory for the Air Forces and is abstracted in reference 53.

Although reference 4 states that in recent years electrical fires have been rare, the National Fire Protective Association (reference 3) cites that out of five fires in flight on commercial air carriers reported between July and November 1946, one was caused by electrical trouble and one by lightning (uncertain).

Flame and Hot Gases

Flames are without question ignition sources. Experimental evidence indicates that hot gas at the exhaust-stack outlet will ignite gasoline fumes; therefore, exhaust gas at normal operating temperatures (from 1300° to 1700° F) (references 37, 54, and 55) must be considered an ignition source.

Engine exhaust systems and combustion-type heaters are the most obvious sources of flame and hot gases, but backfires caused by excessively leaning out the fuel mixture, abrupt power changes, and the malfunctioning of the valve system must also be considered. Induction and exhaust systems are considered by the British of sufficient importance that in combating nacelle fires they inject part of the fire-extinguishing medium into the induction system to help stop the engine and to inert residual unburned fuel (reference 4).

Miscellaneous Ignition Sources

Several possible ignition sources cannot be classified in any of the foregoing categories; for example, compression of trapped gases, friction heating of deflated tires, impact firing of fuel tanks, and oxygen-system explosions. Undoubtedly others exist. A recently concluded study of vacuum-system fires by the Civil Aeronautics Administration (reference 56) describes fires started in the vacuum-pressure pump systems by the compression and repeated working of trapped air. Inadvertently dropped jettisonable fuel tanks have ignited upon impact.

DISCUSSION

Based on the review in the preceding sections of this report of the pertinent available data on the characteristics of the fuel, lubricant, and hydraulic fluid, and on ignition sources, consideration may now be given to extensions of the data that are required to provide a more complete understanding of methods for substantially reducing the fire hazard in airplanes.

From the existing information on the ignition and combustion of aircraft fuels, it might be concluded that major reductions in the aircraft fire hazard could be achieved by the use of a low-volatility fuel. The data show, for example, that the flash point of low-volatility fuel is considerably higher than gasoline and that the spread of flame across a fuel surface is only about one-twentieth as rapid for a low-volatility fuel as for gasoline. Because of these characteristics, the use of low-volatility fuel should reduce both the possibility of fire and the tendency for the rapid and disasterous spread of fire that occurs following a crash or a major engine failure in flight. The likelihood of potential explosive mixtures in aircraft tanks when low-volatility fuels are carried could possibly be overcome by inerting or purging with a gas like helium or nitrogen or with treated exhaust gas. Inerting appears to be a desirable feature, whether the fuel carried is a low-volatility type or a gasoline type, although further data are needed to evaluate inerting systems accurately.

Although both small-scale and large-scale laboratory tests are quite convincing in demonstrating the retarded ignition, slower rate of burning, and generally less explosive character of low-volatility fuel, a question remains as to whether or not a reduction in fire hazard would actually result from the use in aircraft of low-volatility fuel. It seems very doubtful if further bench or model tests of the sort that have been performed will answer this question any more completely than existing data. Consequently, crash tests to establish whether or not significant safety benefits are derived from low-volatility fuel appear to be required for final, convincing evidence. In these tests, multiengine, war-surplus transport aircraft could be crashed, with engines running, from flight or from a ramp or cliff under circumstances closely simulating accident conditions. Alternately, the aircraft would contain first conventional aviation gasoline and then the low-volatility fuel in inerted tanks. A sufficient number of airplanes could be crashed in order to determine by visual observations and recorded data whether or not significant differences in the frequency of fire and in the rate of spread of fire are experienced with the two types of fuel. The difficulty and expense of the crash tests is recognized, but no other technique appears to serve the same purpose.

The practical usefulness of low-volatility fuel as a means of reducing the fire hazard depends not only upon whether or not it results in a significant reduction in the tendency of fire to start and to spread, but upon the service characteristics of engines that are operated on such fuels. Reduction in fire hazard by use of low-volatility fuel must be accompanied by engine reliability at least as good as that now achieved with conventional aviation gasoline. Existing data of the petroleum and engine industries need to be extended to provide conclusive information on the serviceability of engines operating on low-volatility fuel. This information may be obtained in test-stand investigations and in cargo airline operations.

The lubricating oil may ignite first in many fires and constitute the source of ignition for the large bulks of fuel. A significant reduction in the fire hazard may result from the use of noninflammable lubricants and the continued study of the aircraft fire problem may emphasize the advantages of the use of such a material. University and commercial laboratories, particularly in the petroleum industry, have started the development of some of the possible noninflammable lubricants. This phase of the research requires further fundamental investigation, which should include the synthesis of new compounds and experimental evaluation of the characteristics of lubricants in airplane engines.

Although the search for noninflammable hydraulic fluids has been in progress for many years and certain fluids less flammable than conventional fluids have been developed, this branch of the research cannot be considered closed. Materials considered to date either are not entirely suitable or have not had sufficent development effort put on them to demonstrate completely their practicability. Research should be continued until a serviceable and practical material is evolved and used.

As part of a consideration of methods of reducing fire hazards by using less flammable liquids, a discussion of the status of fire extinguishing is appropriate. The investigations by the Civil Aeronautics Administration, the Bureau of Aeronautics, the U. S. Air Forces, and private research laboratories have already made important contributions to the knowledge on this subject. An analysis of the results indicates that a better understanding of the basic chemistry of fire-extinguishing agents is still needed. Research on the influence of aqueous solutions of certain salts in small concentrations on the combustion process has indicated that the fire-extinguishing action was not wholly one of cooling or oxygen dilution, but is explained on the basis of the salt influencing the combustion process. The unexplained difference between the effectiveness of various extinguishing agents indicates that further information is necessary in order to establish the influence of various substances on the chain reactions that occur during combustion. Fundamental investigations are necessary to determine the physical and chemical properties of fire-extinguishing agents required to provide maximum cooling and blanketing action. Parallel development of techniques for reliable and immediate detection of fire or combustible mixtures is also necessary.

Thus far the discussion has been concerned with the characteristics of flammable liquids as they relate to the fire problem. Also vital to the solution of the fire problem is an understanding of the ignition sources. An analysis of existing literature shows that the exhaust system of the airplane may be the single most dangerous ignition source, particularly in a crash or following a major engine failure, at which times combustible vapor and liquids are freely exposed to the hot surfaces. Although some information is available in the literature, further investigations of techniques for cooling of the exhaust-disposal system are necessary. Further data relating the ignitibility of gasoline or oil to the temperature of hot exhaust pipes as a function of the air flow over the pipe are necessary before exhaust systems may be adequately designed.

It must be admitted, however, that other ignition sources, such as residual flame in cylinders, other hot engine parts, and electrical-system failures may have started some of the fires that have been attributed to the exhaust system. It is important that the knowledge on these sources of ignition be extended so that necessary remedial measures may be established.

The origin and propagation of fires resulting from malfunctioning or major failures of engines or accessories is being investigated by the Civil Aeronautics Administration. This research has already provided much information on the ignition sources and the nature of the spread of fires in the airplane, particularly as the hazard manifests itself in flight. Additional detailed information on the ignition characteristics of the airplane's inflammables in conjunction with the airplane's ignition sources is needed. Some of these data may be obtained in a laboratory simulation of the airplane environment. It is recognized that some phases of this work are already under way in the Civil Aeronautics Administration.

Further necessary information on the origin and propagation of fires occurring in accidental airplane crashes could be obtained from intentional airplane crashes. The same sequence of crash tests as those used to prove or to disprove the safety features of low-volatility fuel and other remedial measures should suffice for this purpose. In these crashes, visual and photographic observations should be made and data recorded on temperature histories in the critical zones of the aircraft. Detailed observations on a series of crashes should advance the knowledge on ignition and propagation of fires.

Fuel tanks that reduce the splash and spread of fuel in a crash offer an alternate or complementary solution to the problem of reducing the probability of ignition and the rate of spread of fire. The Civil Aeronautics Administration is working on the development of fuel tanks that have an increased crash resistance. Creative effort should be continued toward the discovery of fuel tank configurations and methods of construction by which the fuel can be contained after a crash.

CONCLUDING REMARKS

The foregoing discussion is concerned with two major fundamental variables in the fire problem, combustibles and ignition sources, in the belief that a significant reduction in aircraft fire hazard is to be obtained by dealing appropriately with them. In conclusion, mention must be made of other and certainly important considerations in the over-all problem of fire safety, such as general airplane layout, aircraft design detail, and service, maintenance, and operational practices.

Layout of the airplane to provide maximum distance between the fuel and the engine, which is believed to be the principal ignition source, may lower the incidence of fires. The mounting of fuel tanks at the tips of the wings is an example of a possible layout. Refinement of detail airplane design with particular emphasis on fire hazard should lead to a safer airplane. Attention might be directed to such things as separating combustibles and ignition sources, exhaust system, plumbing, drains and ventilators, and electrical equipment. Application in design practice should be made of known safety measures to an even greater extent than is being made at present. This, of course, applies equally to service, maintenance, and operational practices. The tackling of many minor details will, as has frequently been pointed out, aid materially in solving the major problem.

The ultimate reduction of the fire hazard will not result from the application of any single improvement, but will come from an integration into the airplane design and flight operation of new ideas and methods, many of which remain to be explored.

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TABLE I - ACCIDENTS SEVERE ENOUGH TO COMPLETELY

WASH OUT AIRPLANE

Fire following crash			No fire following crash		
Date	Total aboard	Fatalities	Date	Total aboard	Fatalities
2- 4-46	4	4	1-31-46	21	21
3- 3-46	27	27	5-29-46	4	0
4-24-46	3	3	7-20-46	4	0
5-16-46	27	27	7-25-46	5	0
8- 9-46	6	4	7-31-46	5	0
8-25-46	2	2	8-21-46	25	2
9- 5-46	21	20	9- 9-46	1	0
9- 7-46	4	4	10-17-46	13	13
10- 3-46	39	39	10-19-46	3	3
10- 8-46	47	2	10-21-46	1	1
10-11-46	26	0	11- 9-46	18	0
10-12-46	8	0	11-11-46	20	2
11-13-46	11	11	11-21-46	2	0
12-24-46	12	12	12- 4-46	17	0
12-28-46	2	2	12-14-46	5	0
12-28-46	23	13	12-17-46	7	7
12-31-46	5	5	12-24-46	45	0
			12-28-46	21	2
Total	267	175 or 66 percent	Total	217	51 or 24 percent

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TABLE II - ACCIDENTS SEVERE ENOUGH TO HAVE AT

LEAST ONE FATALITY

Fire following crash			No fire following crash		
Date	Total aboard	Fatalities	Date	Total aboard	Fatalities
2- 4-46	4	4	1- 6-46	11	3
3- 3-46	27	27	1-31-46	21	21
4-24-46	3	3	8-21-46	25	2
5-16-46	27	27	10-17-46	13	13
8- 9-46	6	4	10-19-46	3	3
8-25-46	2	2	10-21-46	1	1
9- 5-46	21	20	11-11-46	20	2
9- 7-46	4	4	12-17-46	7	7
10- 3-46	39	39	12-28-46	21	2
10- 8-46	47	2			
11-13-46	11	11			
12-24-46	12	12			
12-28-46	2	2			
12-28-46	23	13			
12-31-46	5	5			
Total	233	175 or 75 percent	Total	122	54 or 44 percent

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TABLE III - ACCIDENTS SEVERE ENOUGH TO CAUSE FATALITIES UP TO TWO-THIRDS OF PEOPLE INVOLVED

Fire following crash			No fire following crash		
Date	Total aboard	Fatalities	Date	Total aboard	Fatalities
8- 9-46	6	4	1- 6-46	11	3
10- 8-46	47	2	8-21-46	25	2
12-28-46	23	13	11-11-46	20	2
			12-28-46	21	2
Total	76	19 or 25 percent	Total	77	9 or 12 percent

TABLE IV - ACCIDENTS HAVING AT LEAST ONE FATALITY AND AT LEAST ONE SURVIVOR

Fire following crash			No fire following crash		
Date	Total aboard	Fatalities	Date	Total aboard	Fatalities
8- 9-46	6	4	1- 6-46	11	3
9- 5-46	21	20	8-21-46	25	2
10- 8-46	47	2	11-11-46	20	2
12-28-46	23	13	12-28-46	21	2
Total	97	39 or 40 percent	Total	77	9 or 12 percent

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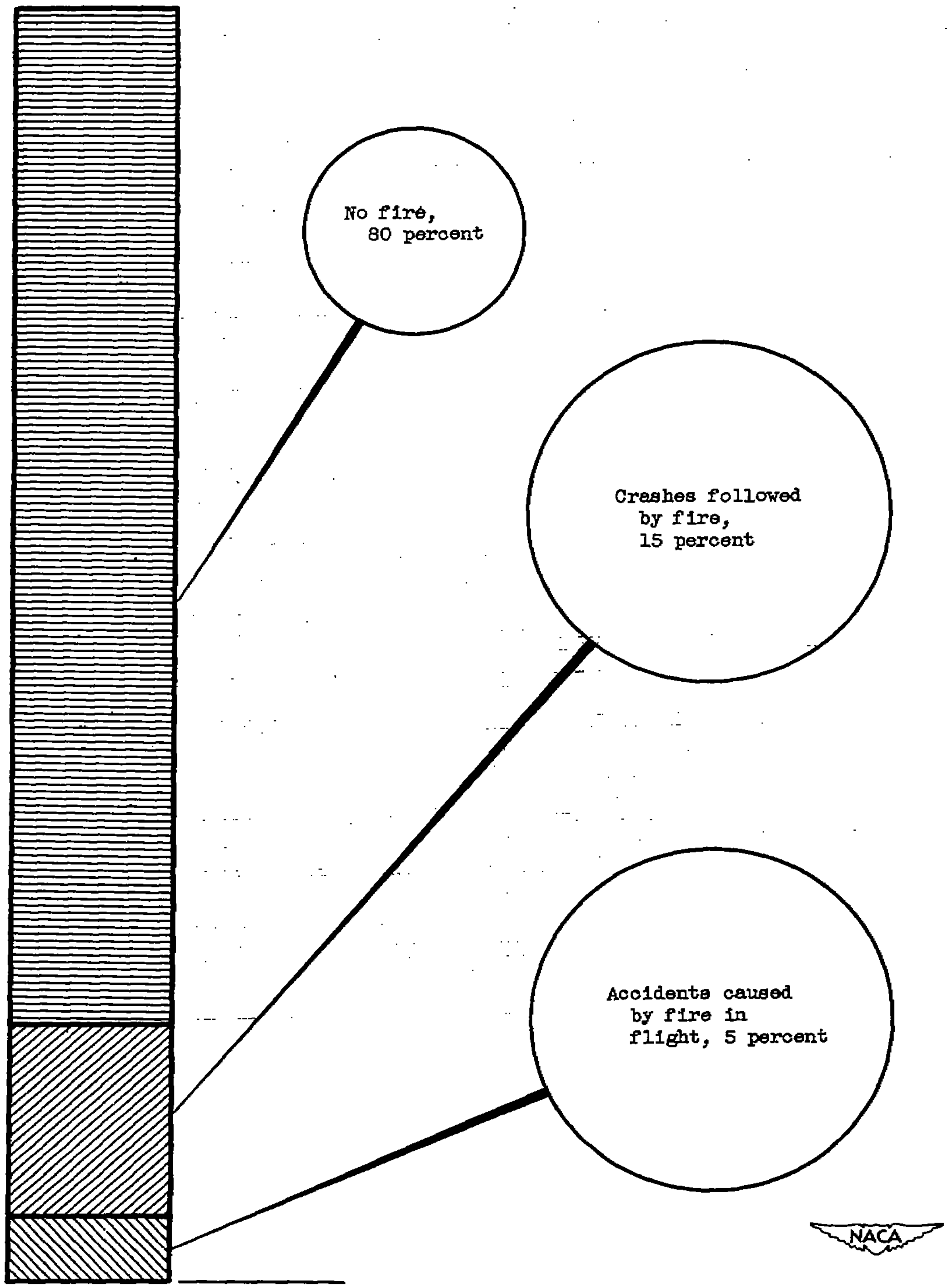


Figure 1. - Percentage of total air-carrier accidents for 1946 in which fire was involved.

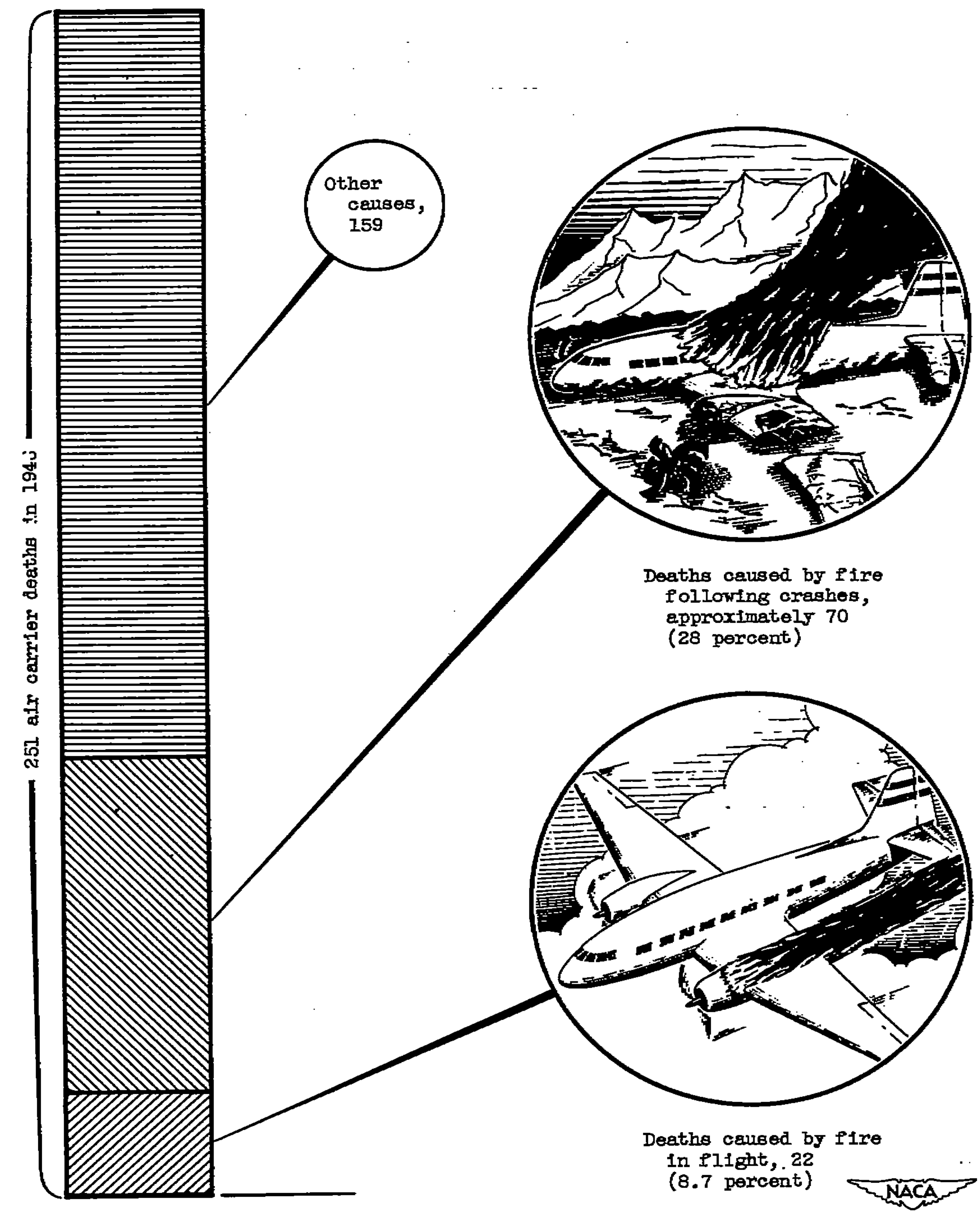


Figure 2. - Comparison of deaths attributed to fire with total deaths in air-carrier accidents for 1946.

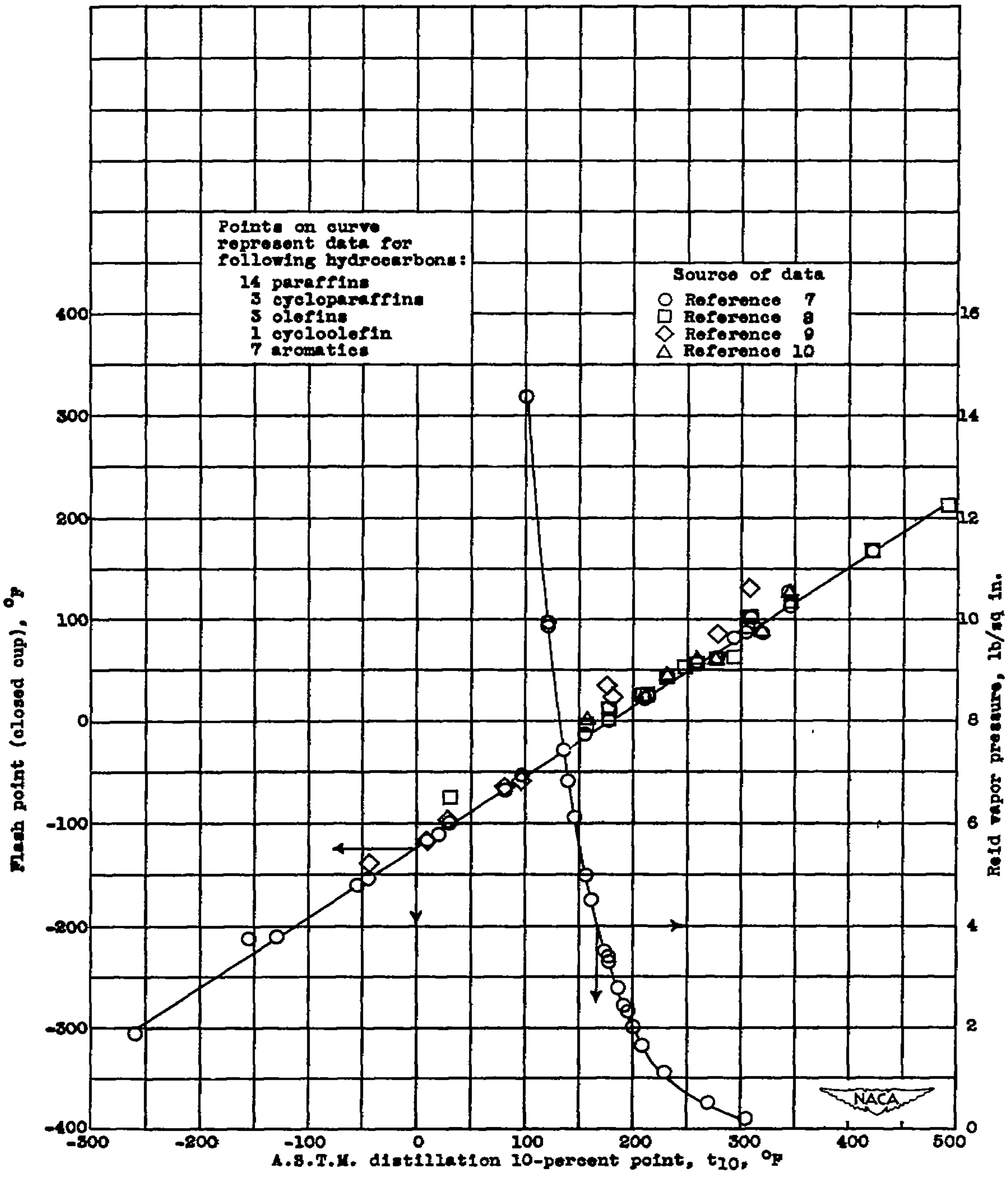


Figure 3. - Relation between flash point and fuel volatility.

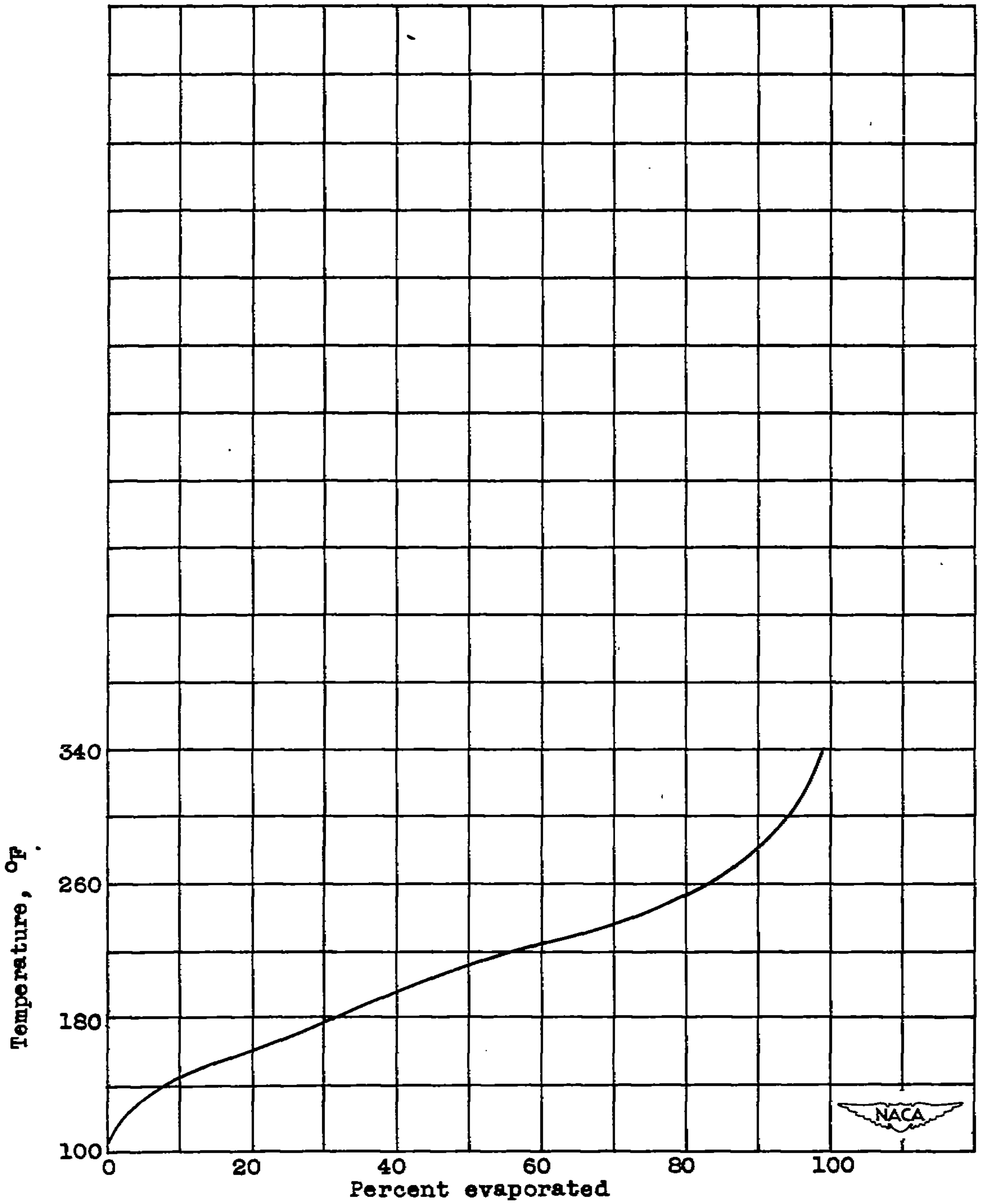


Figure 4. - A.S.T.M. distillation curve for an aviation fuel.

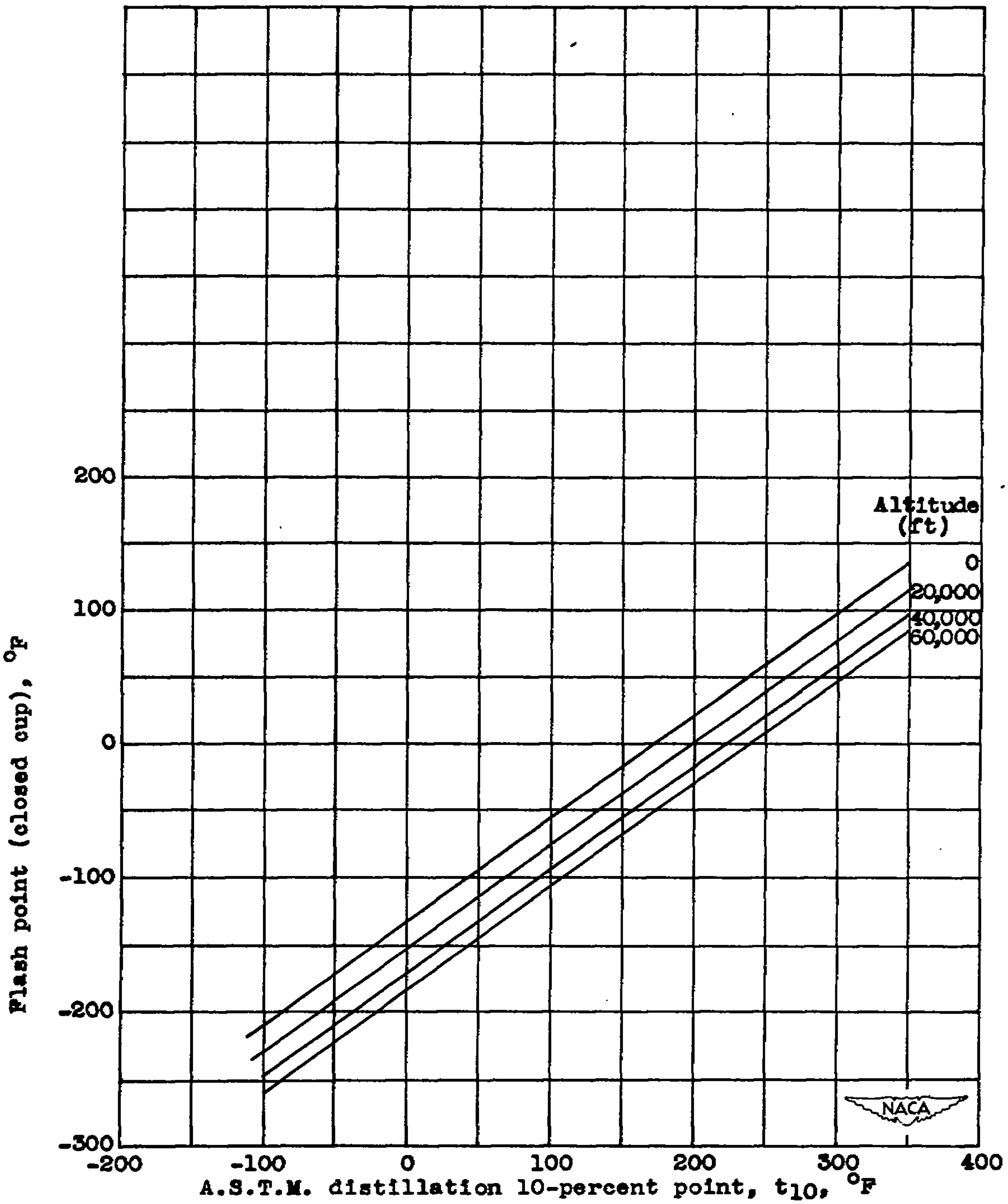


Figure 5. - Relation between volatility and flash point at various altitudes.

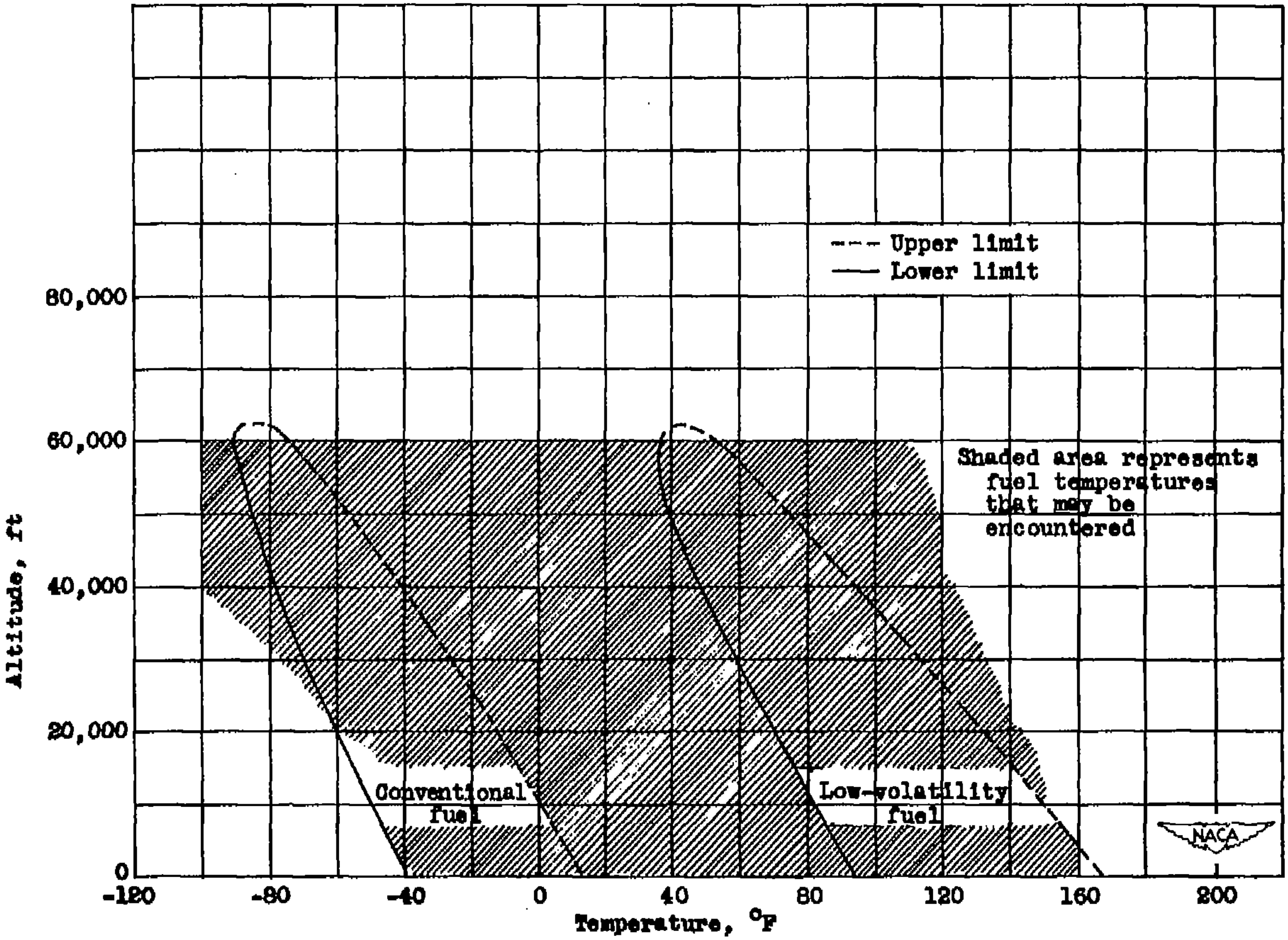


Figure 6. - Inflammability limits of fuels. (California Research Corp. and reference 25)

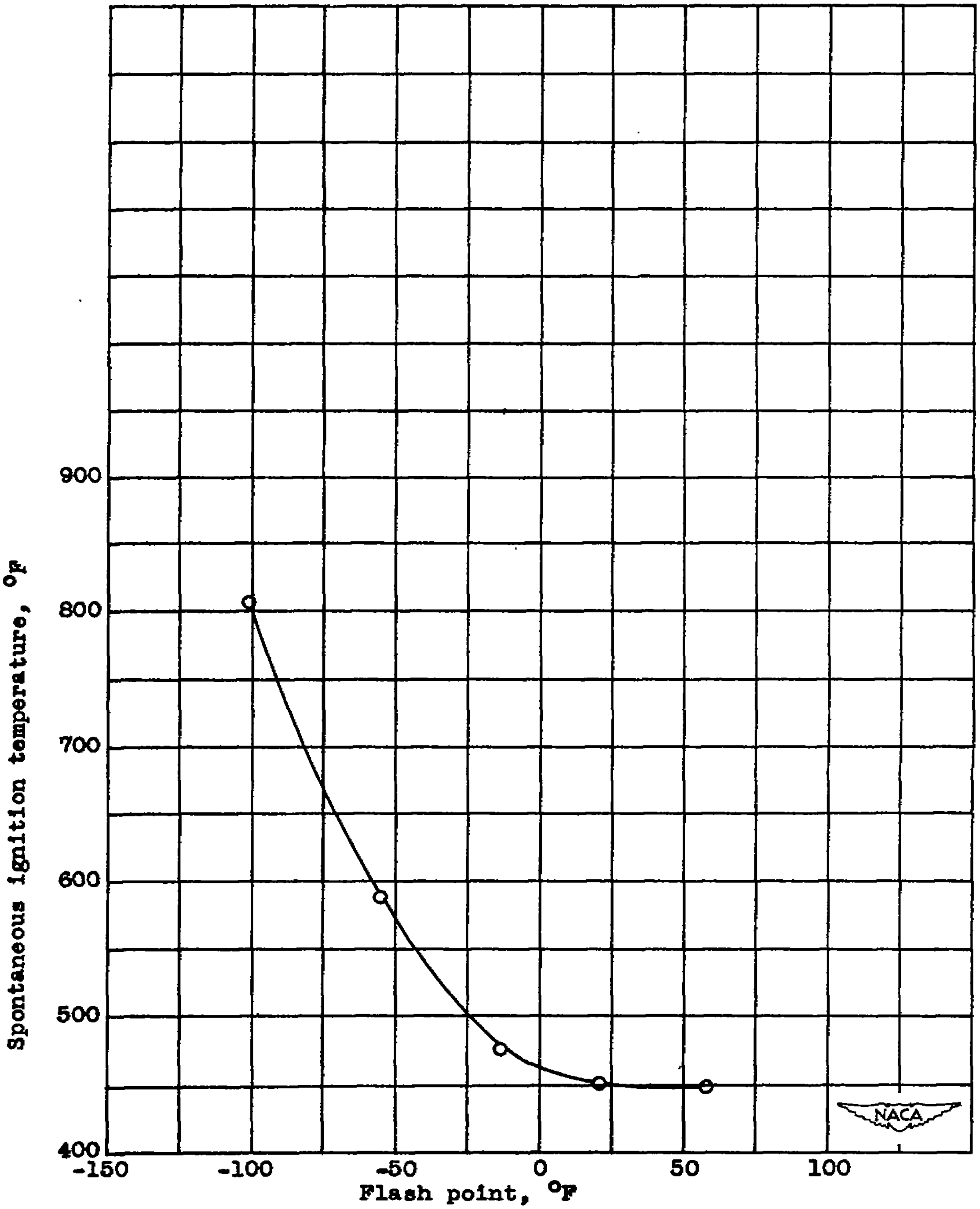
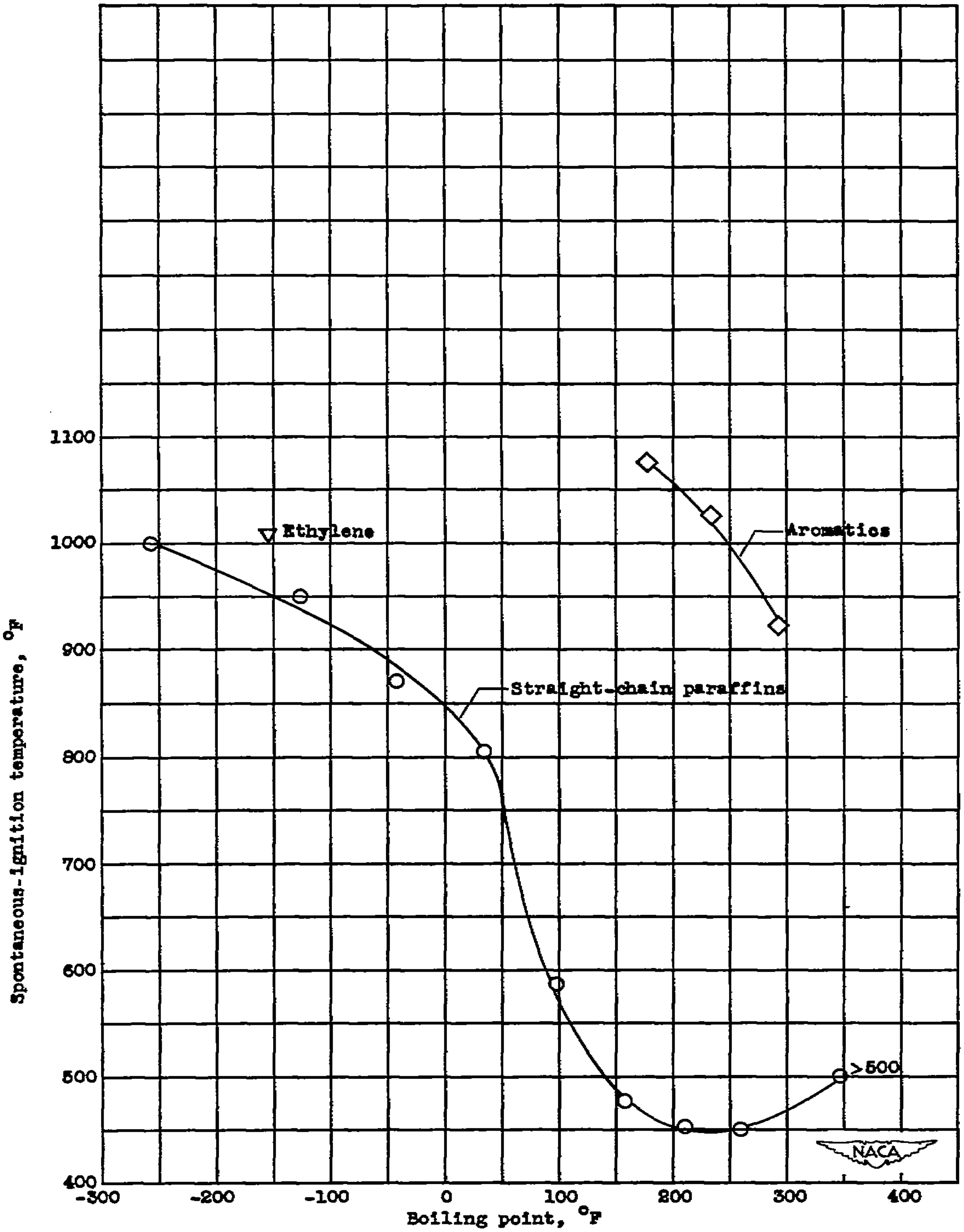
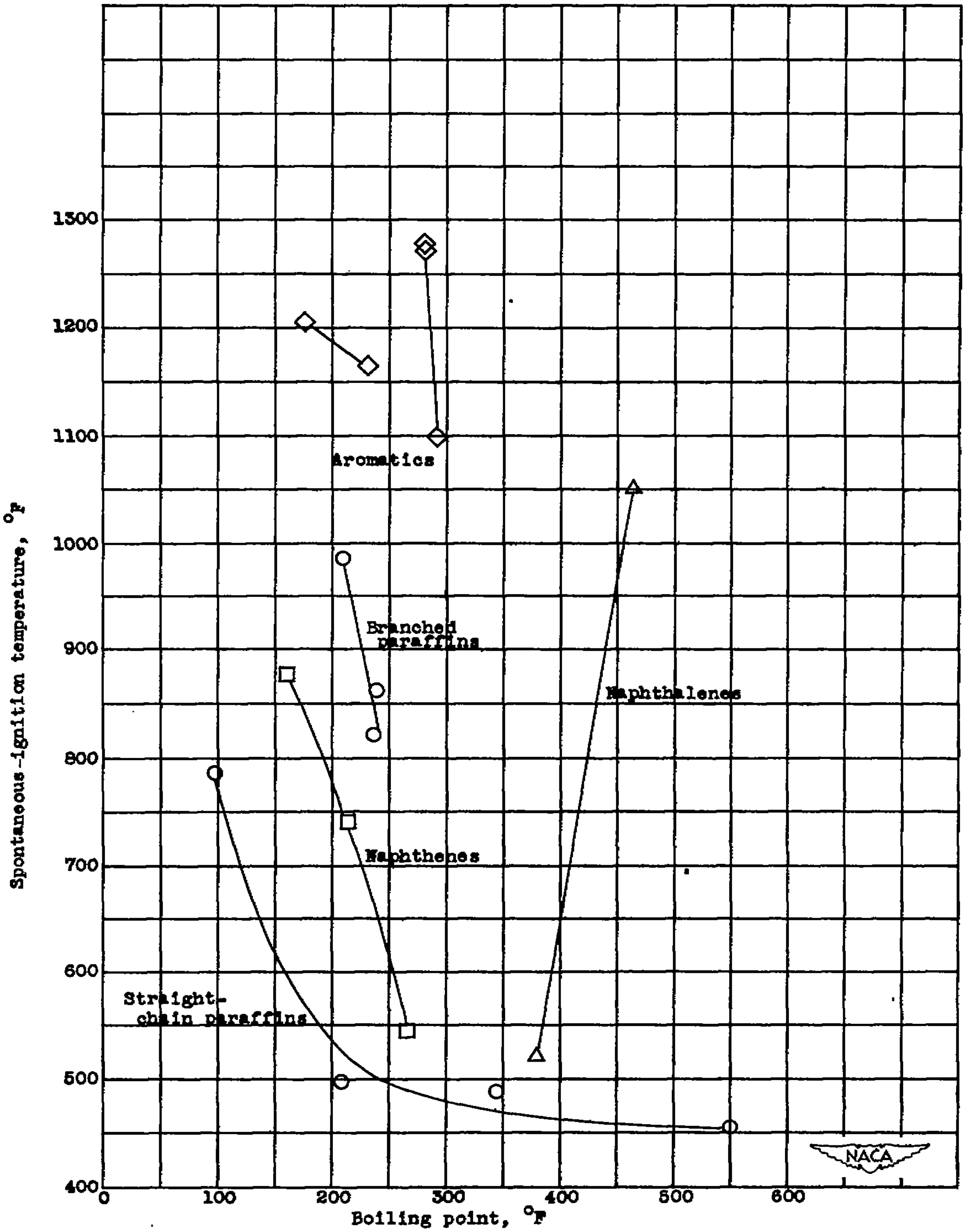


Figure 7. - Relation between spontaneous ignition temperature and flash point for straight-chain hydrocarbons.



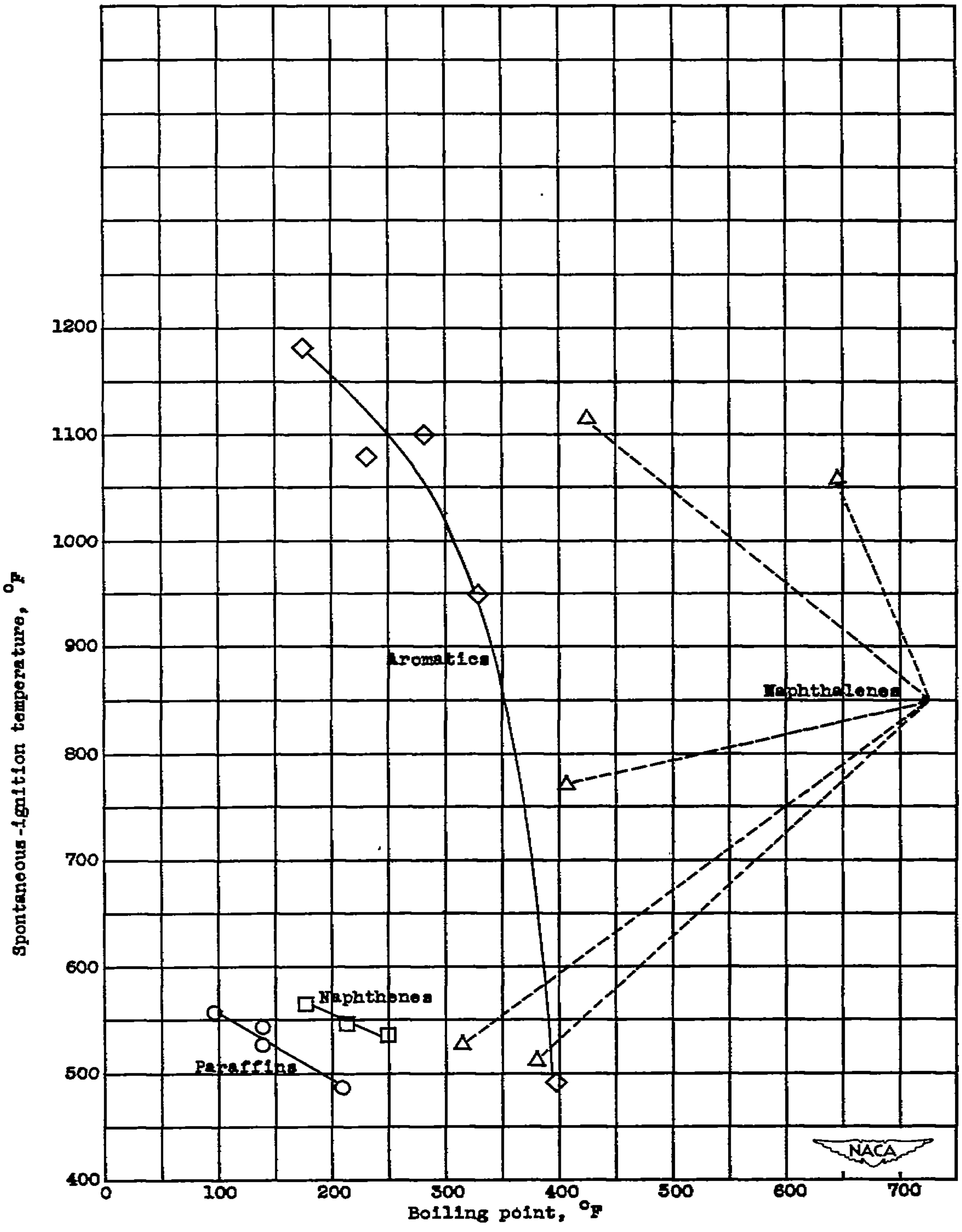
(a) Data from reference 8.

Figure 8. - Spontaneous-ignition temperatures of hydrocarbons.



(b) Data from reference 12.

Figure 8. - Continued. Spontaneous-ignition temperatures of hydrocarbons.



(c) Data from reference 13.

Figure 8. - Concluded. Spontaneous-ignition temperatures of hydrocarbons.

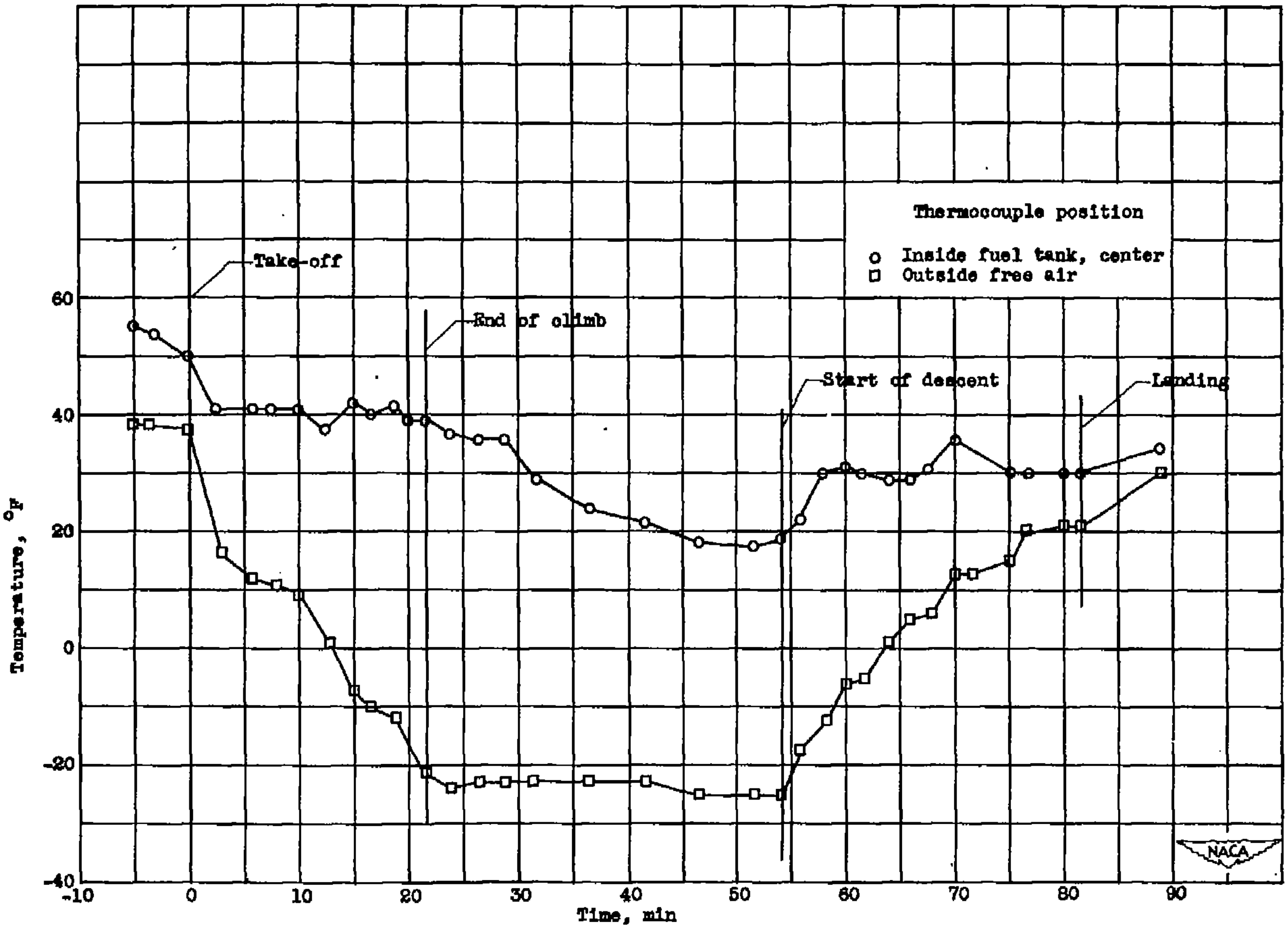


Figure 9. - Temperatures in aircraft fuel tank compared with temperature of outside free air during flight.

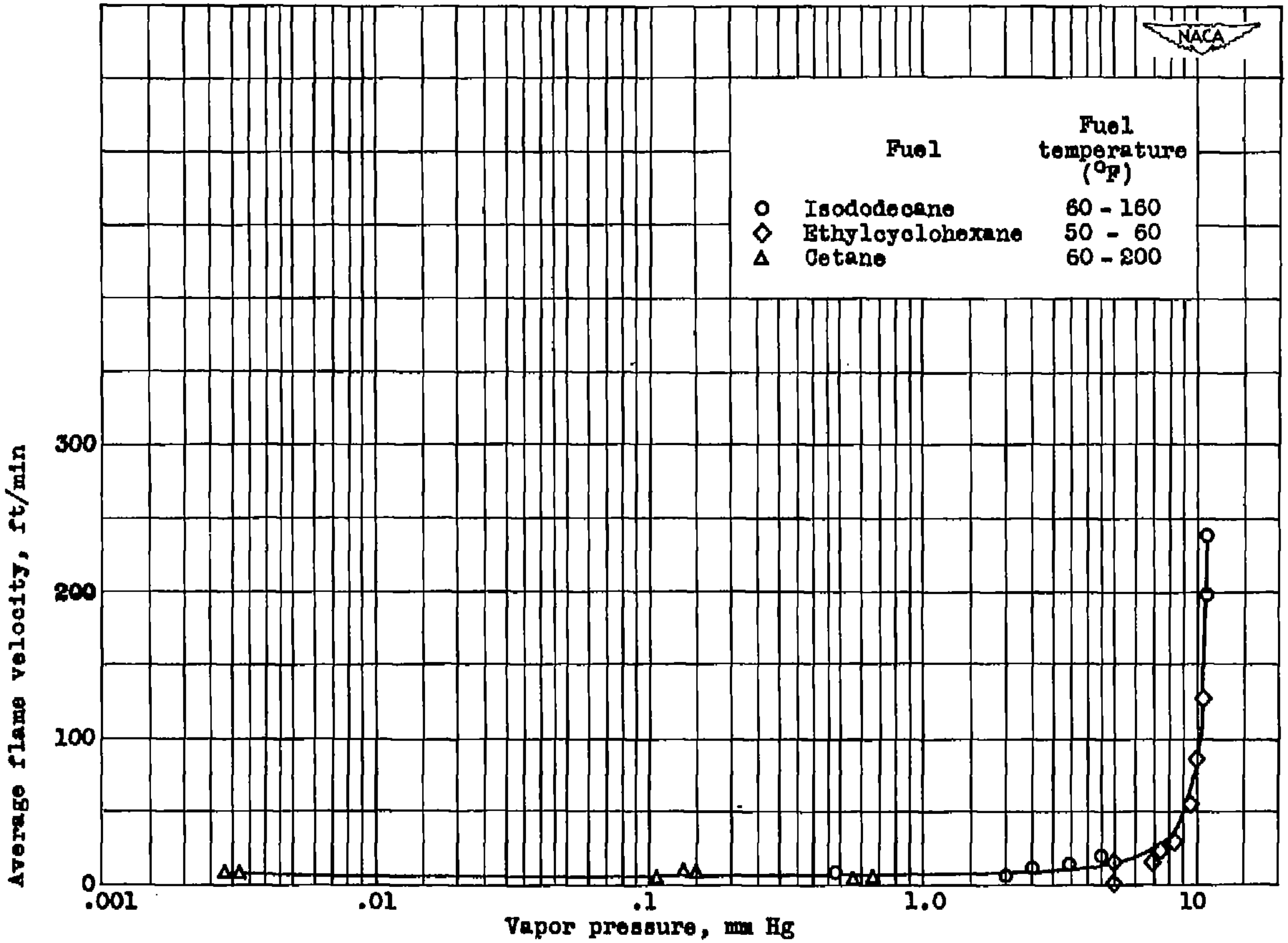


Figure 10. - Effect of fuel vapor pressure on rate of flame spread in open transite trough 48 inches long. (Shell Development Company data)

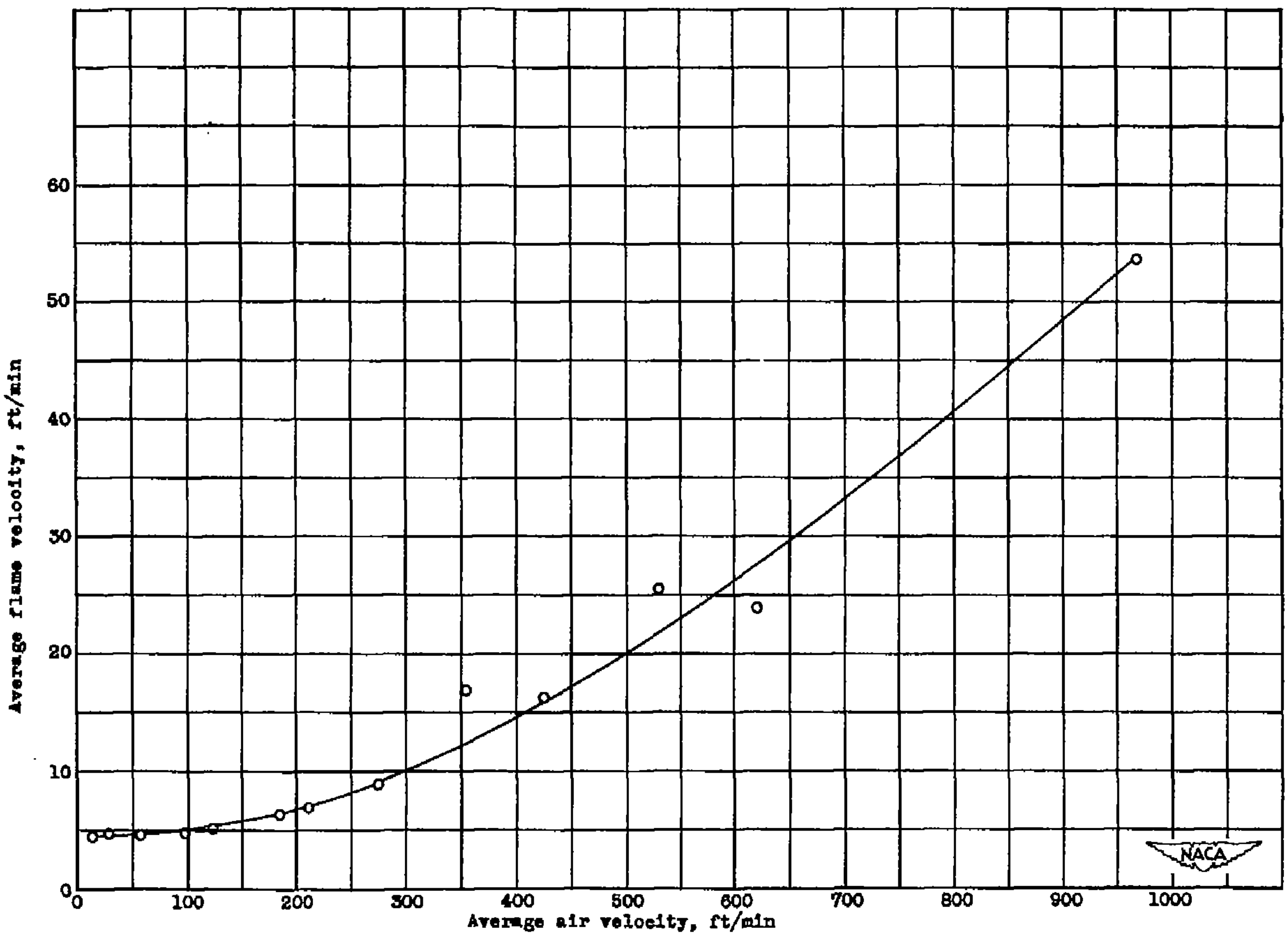


Figure 11. - Effect of air velocity on rate of flame spread in open transite trough. Fuel, isododecane; fuel temperature, 62° F; fuel vapor pressure, 0.9 mm Hg. (Shell Development Company data)

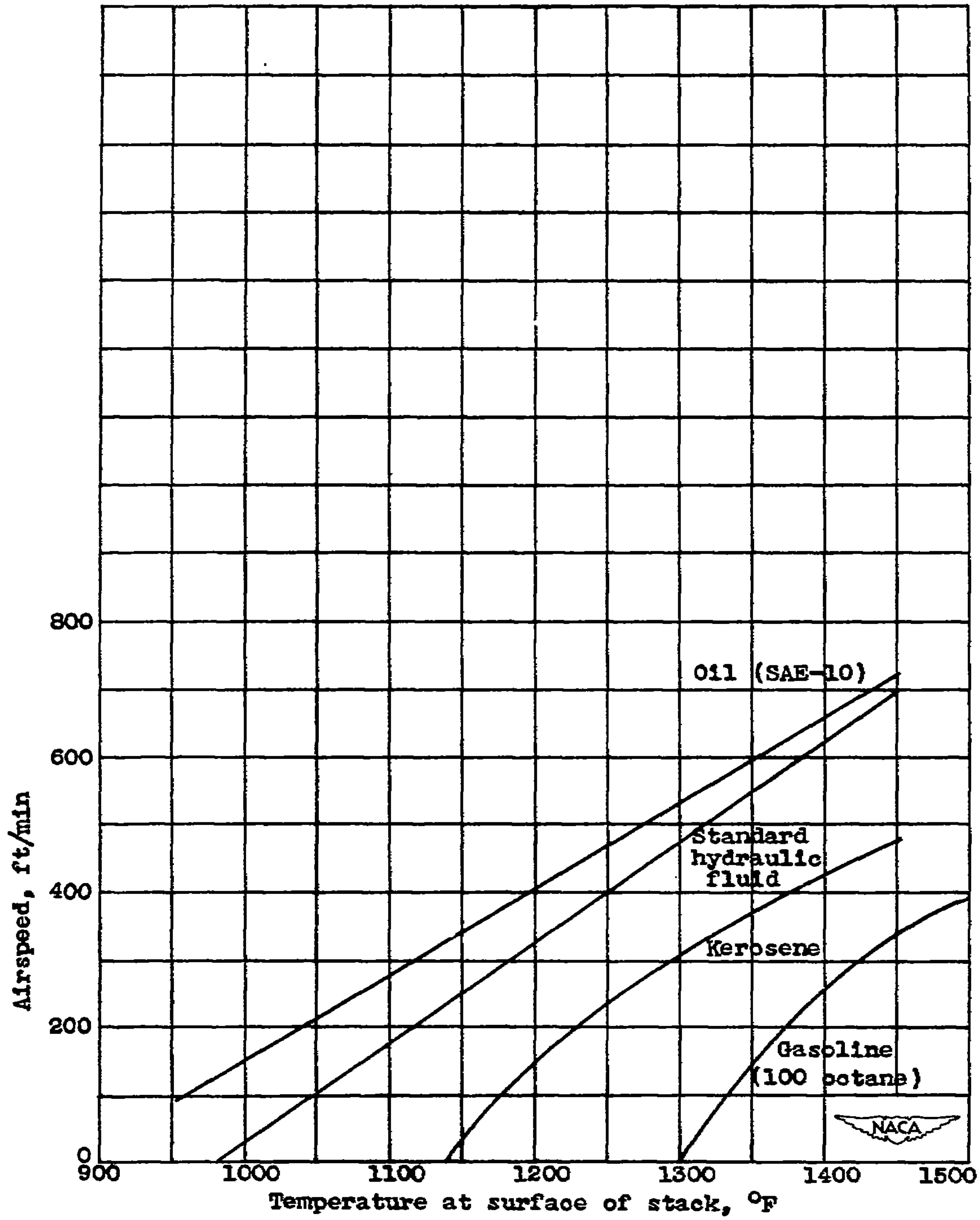


Figure 12. - Relation between temperature and airspeed in a dynamically clean exhaust stack well that will prevent ignition of flammable fluids (CAA data).